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DATA VERSUS INFORMATION

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Karl Javorszky, Alex Hankey, Loet Leydesdorff, Guy A Hoelzer,
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(In order of appearance in the text)

Abstract: *From its very beginnings in early 90’s as an informal endeavor promoted by Michael Conrad and Pedro C. Marijuán, the FIS initiative (Foundations of Information Science) has been an attempt to rescue the information concept out from its classical controversies and use it as a central scientific tool, so as to serve as a basis for a new, fundamental disciplinary development – Information Science [Marijuán, 2017]. The FIS discussion list has been an essential instrument to keep alive the Foundations of Information Science initiative [FIS List, 2017]. This paper presents a part of a concrete discussion about interconnections between concepts “Data” and “Information” which became a step to more clear definitions of both concepts.*

Keywords: *Foundation of Information Science, FIS, Data, Information.*
ITHEA Keywords: *A.1 Introductory and Survey.*

Introduction

There is a naïve and widespread opinion that new machines, mechanisms, and devices appear from out of nowhere. In the beginning, there is nothing — then a great inventor comes along and develops a completely finished something. The Goddess Athena, if we can trust the ancient myth, appeared in the same way. A powerful axe stroke split Zeus’ skull and an unharmed Athena stepped out in full armament. There she stood, with spear and shield, before the surprised eyes of the Olympian Gods [Altshuller, 1999].

Machines, however, do not appear from inside the head of an inventor completely “armed.” Instead, they are born weak; slowly gaining strength by absorbing many inventions [Altshuller, 1999].

The same we may say for new theories. Step by step and due the great effort of many scientists, it is possible to invent and to propose the new knowledge.

From its very beginnings in early 90’s as an informal endeavor promoted by Michael Conrad and Pedro C. Marijuán, the FIS initiative (Foundations of Information Science) has been an attempt to rescue the information concept out from its classical controversies and use it as a central scientific tool, so as to serve as a basis for a new, fundamental disciplinary development – Information Science [Marijuán, 2017]. The FIS discussion list has been an essential instrument to keep alive the Foundations of Information Science initiative [FIS List, 2017].

At FIS, rather than the discussion of a single particularized concept, information becomes the intellectual adventure of developing a “vertical” or “trans-disciplinary” science connecting the different threads and scales of informational processes, which demands both a unifying and a multi-perspective approach. Above all, the solution of the numerous conundrums and conceptual puzzles around information becomes the patient task of a community of scholars, in which the ideas and speculations of each individual thinker can be shared and experienced upon by the other colleagues, so that a sort of “group mind” develops (paraphrasing L. Hyde, 1979): one that is capable of cognitive tasks beyond the power of any single person [Marijuán, 2017].

This paper presents how productive the FIS discussions are on the example of a concrete discussion about interconnections between the concepts “Data” and “Information”, which became a step to more clear definitions of the both concepts. The discussion was provided via FIS List from September 15 till October 08, 2017. In this paper we extract only the posts concerned with the topic above. Several posts are not included in the text below due to lack of permission from their authors. Nevertheless, they had been fruitful and maybe seen in the FIS List archive [FIS Archives, 2017].

The paper is organized as follows: the next four sections present main ideas of the participants in discussion organized in four groups “Thesis” - “Antithesis” - “Discussion” - “Synthesis”. Finally, conclusion and further work sections are given. The body of the paper is given as a dialogue between FIS members. Participant name is indicated for each contribution. Corresponding links to FIS List Archive where the posts are saved are given. All the text with no author indicated (out of the tables) is written by Krassimir Markov.

Thesis

Krassimir Markov (http://listas.unizar.es/pipermail/fis/2017-September/001496.html):

The information is a kind of material reflection and could not be separated from the matter.

Of course, if one believes in God, it could ...

Information is a state of matter which may be recognized by the (live) subject.

Christophe Menant (http://listas.unizar.es/pipermail/fis/2017-September/001538.html):

We can all agree that perspectives on information depend on the context. Physics, mathematics, thermodynamics, biology, psychology, philosophy, AI, ...

But these many contexts have a common backbone: They are part of the evolution of our universe and of its understanding, part of its increasing complexity from the Big Bang to us humans.

And taking evolution as a reading grid allows beginning with the simple.

We care about information ONLY because it can be meaningful. Take away the concept of meaning; the one of information has no reason of existing.

And our great discussions would just not exist. .... Now,

Evolution + Meaning => Evolution of meaning.

As already highlighted this looks to me as important in principles of IS [Menant, 2011, 2017].

The evolution of the universe is a great subject where the big questions are with the transitions:

energy => matter => life => self-consciousness => ...

And I feel that one way to address these transitions is with local constraints as sources of meaning generation.

Krassimir Markov (http://listas.unizar.es/pipermail/fis/2017-September/001539.html):

I agree with idea of meaning. The only what I would to add is the next:

There are two types of reflections:

1. Reflections without meaning called DATA;
2. Reflections with meaning called INFORMATION.

Antithesis

Christophe Menant (http://listas.unizar.es/pipermail/fis/2017-September/001541.html):

However, I'm not sure that “meaning” is enough to separate information from data. A basic flow of bits can be considered as meaningless data. But the same flow can give a meaningful sentence once correctly demodulated.

I would say that:

1) The meaning of a signal does not exist per se. It is agent dependent.

- A signal can be meaningful information created by an agent (human voice, ant pheromone).

- A signal can be meaningless (thunderstorm noise).

- A meaning can be generated by an agent receiving the signal (interpretation/meaning generation).

2) A given signal can generate different meanings when received by different agents (a thunderstorm noise generates different meanings for someone walking on the beach or for a person in a house).

3) The domain of efficiency of the meaning should be taken into account (human beings, ant-hill).

Regarding your positioning of data, I'm not sure to understand your "reflections without meaning".

Could you tell a bit more?

Discussion

Stanley N Salthe (private letter):

The simple answer to your question about data is to note the word's derivation from Latin Datum, which can be compared with Factum.

Yixin Zhong (http://listas.unizar.es/pipermail/fis/2017-October/001547.html):

The discussion on the concept of information is really fundamental and is the central issue to the foundation of information science.

But, may I remind that there are two categories of the concept of information. One is the concept of object information and the other is the concept of perceived information. They are different from, but also related to, each other.

The object information presented by an object is referred as the state of the object and the pattern with which its state varies. It has nothing to do with the subject and is therefore also termed ontological information.

The perceived information that the subject has about the object is the form, meaning, and utility of the object, all of which are perceived by the subject from the object information. The form, meaning, and utility are respectively termed as syntactic, semantic, and pragmatic information.

When talking about "information", you must be clearly aware of which category of the concept you are really mentioning to. Do not make confusion between the two categories of the concept of information.

When talking about the object information, there is only the state/pattern of the object and has no meaning. Only when talking about the perceived information, there will then be the form, meaning, and utility in it.

The data is the carrier, or expression, of the perceived information. So, data is merely the syntactic information, not the semantic information (meaning), and of course not the perceived information as whole.

What we call the "information" is often referred to the meaning of the information that is the semantic information, instead on the information in the sense of Shannon Information.

For more detail please see my paper [Zhong, 2017].

Yixin Zhong (http://listas.unizar.es/pipermail/fis/2017-October/001567.html):

It is not difficult to accept that there are two concepts of information, related and also different to each other. The first one is the information presented by the objects existing in environment before the subject's perceiving and the second one is the information perceived and understood by the subject. The first one can be termed the object information and the second one the perceived information. The latter is perceived by the subject from the former.

The object information is just the object's "state of the object and the pattern with which the state varies". No meaning and no utility at the stage.

The perceived information is the information, perceive by the subject from the object information. So, it should have the form component of the object (syntactic information), the meaning component of the object (semantic information), and the utility component of the object with respect to the subject's goal (pragmatic information). Only at this stage, the "meaning" comes out.

Karl Javorszky (http://listas.unizar.es/pipermail/fis/2017-October/001546.html):

Data is that what we see by using the eyes. Information is that what we do not see by using the eyes, but we see by using the brain; because it is the background to that what we see by using the eyes.

Data are the foreground, the text, which are put into a context by the information, which is the background. The "context" component shows the equivalent alternatives to the data object. This we find by using the commutative symbols which generate groups. The formal definition of the term "information" is as follows:

Let $x = a_k$ => This is a statement, no information contained.

Let $x = a_k$ and $k \in \{1,2,...,n\}$ => This statement contains the information $k \notin \{1,2,\ldots,k-1,k+1,\ldots n\}$.

The approach we are proposing roots in numeric facts and is discussed in [Javorszky, 2014]. Permutations consist of cycles. The enumeration of elements within cycles creates symbols that are both sequential and commutative at the same time.

By using the concepts presented in [Javorszky, 2013], www.oeis.org, and in the FIS chat room, one can understand the 4 variants of logical symbols that can be on 3 places in one triplet, as basic building words of a logical language.

Alex Hankey M.A. (http://listas.unizar.es/pipermail/fis/2017-October/001549.html):

This is a titbit in support of Krassimir Markov.

There was a very interesting paper by Freeman Dyson in about 1970, about which he gave a Colloquium at the MIT Department of Physics which I attended.

Dyson had analyzed data taken from higher nuclear energy levels in particular bands far above the ground state - probably using the Mossbauer effect if I remember rightly, because it has a very high resolution.

Dyson's question was simple: Does the data contain any useful information?

His analysis was that the eigenvalues represented by this selection of data were no different from those of matrix with Random Entries.

The data were equivalent to a set of random numbers.

Dyson therefore concluded that, "The Data Contained No Useful Information' for the purpose of understanding the nuclear physics involved".

Loet Leydesdorff (http://listas.unizar.es/pipermail/fis/2017-October/001552.html; http://listas.unizar.es/pipermail/fis/2017-October/001559.html) :

The search for an intuitive definition of information has led to unclear definitions. In a recent book, [Hidalgo, 2015, at p. 165], for example, has defined "information" with reference "to the order embodied in codified sequences, such as those found in music or DNA, while *knowledge and knowhow* refer to the ability of a system to process information." However, codified knowledge can be abstract and—like music—does not have to be "embodied" (e.g., [Cowan et al, 2000]).

Beyond Hidalgo's position, [Floridi, 2010, p. 21] proposed "a general definition of information" according to which "the well-formed data are *meaningful*" (italics of the author). [Luhmann, 1995, p. 67] posits that "all information has meaning." In his opinion, information should therefore be considered as a selection mechanism. [Kauffman et al., 2008, at p. 28] added to the confusion by defining information as "natural selection."

Against these attempts to bring information and meaning under a single denominator--and to identify variation with selection--I argue for a dualistic perspective (as did Prof. Zhong in a previous email). Information and meaning should not be confounded. Meaning is generated from redundancies ([Bateson, 1972, p. 420]; [Weaver, 1949]) see [Leydesdorff, 2012, Leydesdorff et al., 2017].

Guy A Hoelzer (http://listas.unizar.es/pipermail/fis/2017-October/001553.html; http://listas.unizar.es/pipermail/fis/2017-October/001555.html) :

If you start by explicitly stating that you are using the semantic notion of information at the start, I would agree whole heartedly with your post.

I claim that physical information is general, while semantic information is merely a subset of physical information. Semantic information is composed of kinds of physical contrasts to which symbolic meaning has been attached. Meaningfulness cannot exist in the absence of physical contrast, but physical information can exist independently of sensation, perception, cognition, and contextual theory.

Jose Javier Blanco Rivero (http://listas.unizar.es/pipermail/fis/2017-October/001554.html):

What if, in order to understand information and its relationship with data and meaning, we distinguish the kind of system we are talking about in each case?

We may distinguish systems by their type of operation and the form of their self-organization. There are living systems, mind systems, social systems and artificial systems.

What information is depends on the type of system we are talking about.

Maybe distinguishing between information and meaning in living systems and artificial systems might not make much sense, but it is crucial for social systems. Bits of information codify possibilities of experience and action (following somewhat loosely Luhmanns social systems theory) and meaning crystallizes when a possibility is fulfilled for a particular subsystem (interaction systems, organizations...).

The role of language in social systems is another reason to distinguish information from meaning.

In artificial systems it might make sense to distinguish between data and information, being data everything a computer needs to make a calculations and information the results of those calculations that enable it to do more calculations or to render an output of whatever kind.

So what is information at some stage of the process becomes data on other.

It is obvious that all of these systems operate closely intertwined. They couple and decouple, retaining their specificity.

Robert K. Logan (http://listas.unizar.es/pipermail/fis/2017-October/001570.html):

So now for my definition of information as can be found in the book [Logan, 2014]:

- *Data* are the pure and simple facts without any particular structure or organization, the basic atoms of information,
- *Information* is structured data, which adds meaning to the data and gives it context and significance,
- *Knowledge* is the ability to use information strategically to achieve one's objectives, and
- *Wisdom* is the capacity to choose objectives consistent with one's values and within a larger social context.”

Stanley N Salthe (http://listas.unizar.es/pipermail/fis/2017-October/001572.html) :

In subsumption hierarchy format [Salthe, 2012] :

{facts {data --> information {knowledge {understanding }}}}

Synthesis

Krassimir Markov (http://listas.unizar.es/pipermail/fis/2017-October/001585.html):

I agree with all above! What is missing? Why we could not come to common understanding if practically we all talk about the same phenomenon and share the same idea?

We all agree that there exist two dualistic forms of information ("what is information at some stage of the process becomes data on other"):

- *External information for the agent* (Informational entity, interpreter, human brain, etc.) called "object information" ("data, information without meaning, what we see by using the eyes; physical information; "given" or "revealed" by God; pure and simple facts without any particular structure or organization, the basic atoms of information!");
- *Internal information for the agent* (interpreter, human brain, etc.) called "perceived information" ("syntactic information + semantic information + pragmatic information; seen by using the brain; semantic information; structured data, which adds meaning to the data and gives it context and significance!").

What we have is the equation: *"Internal information"* =

= *"external information reflected by the agent"* + *"subjective for the agent meaning (or semantic)"*.

But, the internal information for one agent is external for all others and has no meaning (semantic) for them until they reflect it anyway (via some secondary reflections created in the environment by the first agent) and add a new meaning.

This way we have seen that the meaning (semantic) is separated from the external and internal information and exist only in a special case. I.e. we have the same phenomenon in both cases plus some agent depended reaction - adding the meaning ("semantic; structured data, which adds meaning to the data and gives it context and significance").

Finally, the problem with naming the pointed phenomenon has risen. I prefer to call it a "reflection" because of way it is generated - by reflection from the environment via all possible sensors of the agent.

Now, it is not good for me (Occam's razor!) to use name "information" for all the cases pointed above (External information and Internal information). I prefer to use concept "information" only in the second case - Internal information. For the first case (External information) I prefer to use concept "Data".

So, we come to what I had written:

Data = Reflection;

Information = Reflection + Meaning

Further work

Sungchul Ji (http://listas.unizar.es/pipermail/fis/2017-October/001589.html):

Recent discussion on *information* on this list reminds me of one of the main principles of signs advanced by Ferdinand de Saussure (1859-1913) -- *the arbitrariness of linguistic signs.* In contrast, Peirce (1839-1914), a chemist-turned-logician-philosopher, seems to have succeeded in capturing the universal features of all signs, however fleeting, both linguistic and otherwise.

The power and utility of the Peircean definition of signs can be illustrated by applying his triadic definition of signs to the term, 'information', viewed as a sign (having an arbitrary meaning, according to Saussure). My impression is that all the varied definitions of information discussed on this list (which supports the Saussre's principle of the arbitrariness of signs) can be organized using the ITR (Irreducible Triadic Relation) diagram embodying the Peircean principle of semiotics. This is done in Figure 1 below, using the definition of 'information' that Professor Zhong recently provided as an example. As you can see, the ITR template has 6 place-holders, 3 nodes and 3 arrows, which can be populated by more than one set of concepts or terms, as long as the terms or concepts are consistent with one another and obeys well-established laws of physics and logic.

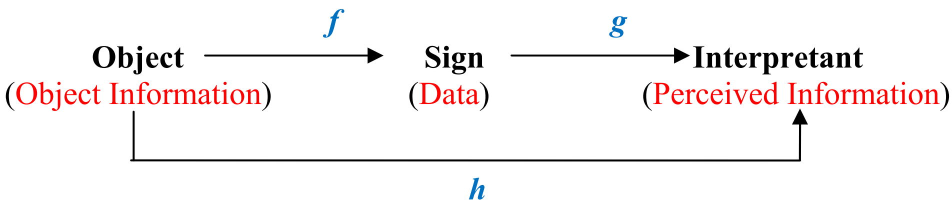

Figure 1. A suggested definition of 'information' based on the triadic definition of the sign proposed by Peirce (1839-1914). The symbol, A --- > B, reads as "A determines B', 'A leads to B', ' A is presupposed by B', 'B is supervened on A' (http://www.iep.utm.edu/superven), etc.

f = natural process (or *information production*)

g = mental process or computing (or *information interpretation*)

h = correspondence (or *information flow*)

Object = Something referred to by a sign (or intrinsic information*)

Sign = Something that stands to someone for something other than itself in some context. Also called 'representamen' (or referential information*)

Interpretant = The effect a sign has on the mind (or state) of the interpreter (human or non-human) (or normative information*)

*) These terms discussed by T. Deacon on FIS list [Deacon, 2017] are added in proof to indicate that they are another example of the irreducible triadic relation (ITR) of Peirce.

Mark Johnson (http://listas.unizar.es/pipermail/fis/2017-October/001591.html):

Which "information paradigm" is not a discourse framed by the education system? The value of the discussion about information - circular though it appears to be - is that we float between discourses. This is strength. But it is also the reason why we might feel we're not getting anywhere!

A perspective shift can help of the kind that Gregory Bateson once talked about. When we look at a hand, do we see five fingers or four spaces? Discourses are a bit like fingers, aren't they?

Christophe Menant (http://listas.unizar.es/pipermail/fis/2017-October/001599.html):

We should indeed be careful not to focus too much on language because 'meaning' is not limited to human communication. And also because starting at basic life level allows addressing 'meaning' without the burden of complex performances like self-consciousness or free will. (The existing bias on language may come from analytic philosophy initially dealing with human performances).

Interestingly, a quite similar comment may apply to continental philosophy where the 'aboutness' of a mental state was invented for human consciousness. And this is of some importance for us because "intentionality" is close to "meaning". Happily enough "bio-intentionality" is slowly becoming an acceptable entity [Menant, 2015]. Regarding Peirce, I'm a bit careful about using the triadic approach in FIS because non human life was not a key subject for him and also because the Interpreter which creates the meaning of the sign (the Interpretant) does not seem that much explicit or detailed.

Krassimir Markov (http://listas.unizar.es/pipermail/fis/2017-October/001592.html):

I agree with your considerations!

Let me remark that the General Information Theory [Markov et al. 2007] is much more than a single concept. What is important now is to finish this step and after that to continue with the next. It may be just the idea about meaning.

What we have till now is the understanding that the information is some more than data.

In other words:

d = r ;

i = r + e

where:

d => data;

i => information;

r = > reflection;

e => something ***Else***, internal for the subject (interpreter, etc.).

And at the end, the same, but very important form:

i = d + e

Conclusion

Yixin Zhong (http://listas.unizar.es/pipermail/fis/2017-October/001588.html):

The proposed formulas in summary are good. May I mention that the following formulas will be more precise:

Object Info = External info = Syntactic info = Data

Perceived info = Internal info = Syntactic info + Semantic info + Pragmatic info

In other words, data is also a kind of information - called syntactic information, the information without meaning and utility associated. And therefore we have a uniform concept of information.

David Kirkland (http://listas.unizar.es/pipermail/fis/2017-October/001597.html):

Data (that which is given) is objective: the combination of discrete entities or disturbances (energy bundles, photons, sounds, numbers, letters etc) ....

and...

Information (that which is created) is subjective: 'collated or interpreted data' dependent upon, and possibly existing uniquely in, the eye/mind of each beholder. (your Else)

Gordana Dodig-Crnkovic

Let me start with a meta comment: I find the idea of publishing FIS exchanges very good and hope that it will attract attention of the wider readership and inspire colleagues to join the list.

My next comment is about the function of "data". Sociologists collect "data" about social phenomena, and those "data" are not in the form of pixels, counts, signals or symbols. Sociologists treat interviews, video-recordings, and any other type of empirical evidence as "data". It is input that informs their explanatory framework that is on a higher level of abstraction than constructions of theories in fundamental sciences.

What constitutes "data" and information depends on the role of this input for the receiver. It agrees with the view of Jose Javier Blanco Rivero who argues:

"So what is information at some stage of the process becomes data on other. It is obvious that all of these systems operate closely intertwined. They couple and decouple, retaining their specificity."

Karl Javorszky focus on context of application, when he argues that general formula such as $x = a_i$ contains no information, while the statement $x = a_i$ with $i \in \{1,2,...,n\}$ contains information because it limits i to certain range of values.

The above argument refers to an agent who intends to act upon information provided by the first statement, and the action is possible when in general formula concrete data are substituted.

In other words, as Freeman Dyson said:

"The data contained no useful information for the purpose of understanding the nuclear physics involved" as quoted by Alex Hankey (Emphasis added)

Information **for the purpose** is different from **the information that describes an object** (which Algorithmic information theory of Solomonoff and Chaitin provide in the form of shortest program needed to describe/generate data structure).

Information is relational. **It is agent-dependent** and when it is "objective", it is inter-subjective in a strict and well-controlled way. It is important to elucidate how "objectivity" is construed in sciences. One important aspect that is left outside this discussion is information dynamics: how the process from "objective" to meaningful information unfolds in the world, see [Dodig-Crnkovic, 2012].

David Kirkland's makes short summary: *"Data (that which is given) is objective. Information (that which is created) is subjective."*

It should be read in the light of the above characterization of "objectivity". Characterizing information as "subjective" refers to the cognitive process of data transformation and integration in a cognizing agent. That subjective information is then checked with other agents in order to reach inter-subjective validation of information. For non-human agents acting on misinformation eliminates an organism, so there is a tendency, favorable for survival, of using correct information.

In his post (http://listas.unizar.es/pipermail/fis/2017-October/001566.html, not included in this paper) Lars-Göran Johansson adviced: "We can proceed with scientific research, using any information concept we think useful, without assuming it refers to anything." is applicable as long as we are not forced to communicate between disparate scientific frameworks that all use concept of information and define it in different ways. However today we are learning from other research fields – we want to incorporate mathematical theory, computing, physics, biology, neuroscience and cognitive science, networks, ecology and philosophy – this situation is visible from FIS discussions – and all of them use the concept "information" but in different ways. What we are searching is to build connections, translations, bridges, we want to know how "information" processed in the neuron is different from the information processed in a bacterium is different from information communicated via computers with or without people in the loop.

In his post, Terrence W. Deacon [Deacon, 2017] addresses the problem of multiplicity of concepts of information and calls for more careful study of context: "try to agree about **which different uses of the information concept are appropriate for which contexts.**" This implies to search for explication of underlying assumptions for different concepts of information as they are used in different contexts. One step in this direction is an attempt to make information taxonomy [Burgin and Dodig-Crnkovic, 2017]

Majority of discussions still presuppose that when we say "information" we think of human communication. See e.g. the Oxford dictionary definition of information: https://en.oxforddictionaries.com/definition/information .

It does not mention information in the rest of the natural world such as bacterial or plant communication via "chemical languages".

Finally, this article presents both the discussion about data vs. information as well as the existence of variety of different concepts of information and touches upon the notion of "meaning" and relationship between "objective" information in the world or information carrier and subjective/intersubjective information in cognizing agents (that in principle can be any leaving organism even though discussion still centers on humans).

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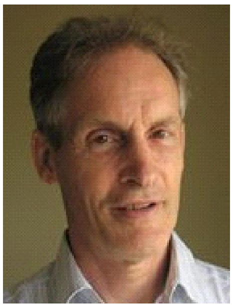

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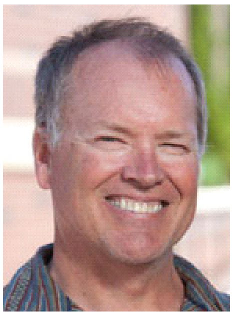

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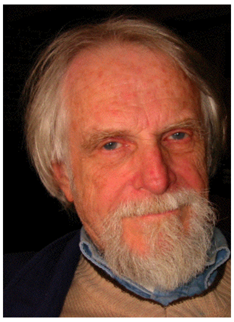

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FRACTAL IMAGE COMPRESSION OF GRAYSCALE AND RGB IMAGES USING DCT WITH QUADTREE DECOMPOSITION AND HUFFMAN CODING

Moheb R. Girgis and Mohammed M. Talaat

***Abstract**: Fractal image compression (FIC) is a well-known technique for image compression, but it suffers from slow encoding process. To improve the efficiency of FIC, hybrid encoding methods that combine fractal coding with other coding methods are used. This paper presents proposed hybrid FIC algorithms, for both grayscale and RGB images, which combine the Discrete Cosine Transform (DCT) with the Quadtree decomposition and Huffman coding techniques. The Quadtree decomposition method is used for the reduction of the search space and Huffman coding is used for improving the compression quality. The DCT is combined with the Quadtree decomposition and Huffman coding to improve the compression ratio. The paper also presents the results of the experiments that have been conducted to evaluate the effectiveness of the proposed hybrid FIC algorithms for grayscale and RGB images.*

***Keywords**: Fractal image compression, Quadtree decomposition, Huffman coding, Discrete Cosine Transform, Hybrid fractal coding methods.*

***ITHEA Keywords**: H. Information Systems: H.3 Information Storage and Retrieval, H.3.2 Information Storage.*

Introduction

As the Internet is growing at an exponential rate, the amount of digital data being transferred, such as images, from one site to another has increased dramatically. There is now, more than ever, a need for quick data transfer methods and more efficient use of memory space. Since images require significantly large amount of memory, they are not transmittable quickly. Compression techniques are used to enable storing an image with much less memory than it would normally require, hence allowing it to be transmitted more quickly.

Fractal Image Compression (FIC) is a well-known technique for image compression. It exploits the self-similarity property efficiently by means of block self-affine transformations to generate a fractal code [Barnsley, 1988], [Jacquin, 1992], [Jacquin, 1993], [Fisher, 1994]. Most FIC techniques can compress a natural image at high compression rates. One of these techniques is based on a mathematical theory called iterated function systems (IFS) [Barnsley and Demko, 1985].

The main problem with fractal compression encoding is that it takes too much time. Therefore combining fractal coding and other coding methods becomes an important direction of fractal compression methods, in order to reduce the encoding time, while achieving better PSNR value and higher compression ratio. Several hybrid FIC methods have been proposed in the literature, such as, FIC with quadtree method for grayscale images [Fisher, 1994], [Ali and Mahmood, 2006]; FIC using quadtree decomposition and parametric line fitting method for synthetic images [Khan and Ohno, 2007]; FIC using quadtree decomposition with Huffman coding method for grayscale images [Veenadevi and Ananth, 2012], and for color images [Pandey and Seth, 2014]; hybrid image compression scheme for color images using DCT and FIC [Rawat and Meher, 2013]; FIC using quadtree decomposition and Discrete Wavelet Transform (DWT) method for color images [Chetan and Sharma, 2015]; and FIC using Discrete Cosine Transform (DCT) and quadtree decomposition with Huffman encoding method for grayscale images [Padmavati and Mesharam, 2015].

In this paper, we present six proposed hybrid FIC algorithms, for grayscale and RGB images, which combine the DCT with the quadtree decomposition and Huffman coding techniques. The quadtree decomposition method is used for the reduction of the search space and Huffman coding is used for improving the compression quality [Pandey and Seth, 2014]. The DCT is combined with the quadtree decomposition and Huffman coding to improve the compression ratio, [Padmavati and Mesharam, 2015].

The rest of the paper is organized as follows: Sections 2 to 5 give brief descriptions of the FIC technique, quadtree decomposition technique, Huffman coding technique, and DCT, respectively. Section 6 presents the hybrid FIC algorithms for grayscale images (Quadtree, Quadtree-Huffman, proposed DCT-Quadtree, and proposed DCT-Quadtree-Huffman). Section 7 presents the proposed hybrid FIC algorithms for RGB images (Quadtree, Quadtree-Huffman, DCT-Quadtree and DCT-Quadtree-Huffman). Section 8 presents the results of the experiments that we have conducted to evaluate the presented hybrid FIC algorithms. Section 9 presents the conclusion of the work presented in this paper, and some points for future work.

Fractal Image Compression

In FIC, the image is firstly divided into a number of square blocks called ranges, and then the image is divided into bigger square blocks, called domains, such that the domain is four times larger than the range [Fisher, 1995]. Next, the domains are mapped to ranges using contractive affine transformations, then the domains are searched for the best match for every range, and the parameters representing the corresponding fractal affine transformation will form the fractal compression code. For every range, the number of the appropriate domain and the fractal compression code are stored. Hence the compression is achieved by storing only the parameters instead of the range. The decoder performs a number of iterative operations in order to reconstruct the original image [Veenadevi and Ananth, 2012].

The advantages of FIC include: good mathematical encoding frame, resolution-free decoding, high compression ratio, and fast decompression. On the other hand, it suffers from slow encoding process [Ali and Mahmood, 2006]. So, the main aim of the research in this area is to achieve better PSNR value, higher compression ratio, and reduce long encoding time without hindering the image quality. To improve the efficiency of FIC, hybrid encoding methods that combine fractal coding with other coding methods are used [Veenadevi and Ananth, 2012].

Quadtree Decomposition Technique

Quadtree decomposition is a representation of an image as a tree in which each node corresponding to a square portion of the image contains four sub-nodes corresponding to the four quadrants of the square, and the root of the tree is the initial image. The basic quadtree decomposition technique works as follows. After some initial number of quadtree partitions are made (corresponding to a specified minimum tree depth), the squares (ranges) at the nodes are compared with domains in the domain pool D, which are twice the range size. The pixels in the domain are averaged in groups of four so that the domain is reduced to the size of the range and the affine transformation of the pixel values is found that minimizes the root mean square (RMS) difference between the transformed domain pixel values and the range pixel values. All the potential domains are compared with a range. If the resulting RMS value is above a specified threshold and if the depth of the quadtree is less than a specified maximum depth, then the range is subdivided into four quadrants, which means adding four sub-nodes to the node corresponding to the range, and the process is repeated. If the RMS value is below the threshold, the optimal domain and the affine transformation on the pixel values are stored. The collection of all such transformations forms the encoding of the given image. [Fisher, 1995]

Huffman Coding Technique

Huffman coding is one of the most popular techniques for removing coding redundancy, which has been used in various compression applications, including image and video compression. It utilizes the statistical property of alphabets in the source stream, and then produces respective binary codes for these alphabets, called code words. These code words are strings of bits of variable length, i.e., their lengths are not fixed like ASCII. The code words for alphabets having higher probability of occurrence are shorter than those code words for alphabets having lower probability. Thus, Huffman coding is based on the frequency of occurrence of a data item (pixel or small blocks of pixels in images) [Aarti et al., 2013]. Code words are stored in a Code Book (or Dictionary), which is constructed for each image. The code book plus encoded data must be transmitted to enable decoding.

Huffman Encoding: The Huffman encoding algorithm starts by creating a list of all symbols, sorted by their frequencies (or probabilities of frequencies of occurrence) in descending order. Next, the two smallest frequency values are combined and deleted from the list, and then the new value is sorted into the list. This process is repeated until all the frequencies have been added up. The final number at the head of the tree should be the sum of all the frequencies. The code word of each symbol is traced from the top of the tree, noting the path taken at each fork. At each fork, the higher frequency edge is designated by a “1” and the lower frequency edge by a “0”, [Lee, 2007]. Thus, an extremely large string of symbols can be shown as a small list of binary encoded strings. It will be no any ambiguity in decoding, as no code word is a prefix of any other code word. In Huffman encoding of images, a symbol represents an image block.

Huffman Decoding: Given the encoded (compressed) data and the code book generated by the Huffman encoder, the Huffman decoder can decompress the data. Any Huffman encoded string can be decoded by examining the individual bits of the string in a left to right manner. The algorithm for decoding is simple. Start at the root of the Huffman tree and read the first bit off the input (compressed) file. If it is zero, follow the left edge of the tree; if it is one, follow the right edge. Read the next bit and move another edge toward the leaves of the tree. When the decoder arrives at a leaf, it finds there the original, uncompressed symbol, and that code is emitted by the decoder. The process starts again at the root with the next bit. [Veenadevi and Ananth, 2012]

Discrete Cosine Transform

The Discrete Cosine Transform (DCT) is the key to the JPEG baseline compression process. The DCT is a mathematical function that takes a signal and transforms it from one type of representation to another. For example, an image is a two-dimensional signal that is perceived by the human visual system. The DCT converts the signal (spatial information) into numeric data ("frequency" or "spectral" information) so that the image’s information exists in a quantitative form that can be manipulated for compression. [Lossy Data Compression JPEG, 2017].

DCT separates images into parts of different frequencies where less important frequencies are discarded through quantization and important frequencies are used to retrieve the image during decompression. DCT is applied to every non-overlapping block of the image. The DCT is performed on an N x N square matrix of pixel values, ***f(x,y),*** and it yields an N x N square matrix of frequency coefficients, ***DCT(i,j)***. The formula for the two-dimensional DCT is as follows:

$$DCT(i,j) = \frac{1}{\sqrt{2N}} C(i)C(j) \sum_{x=0}^{N-1} \sum_{y=0}^{N-1} f(x,y) COS\left[\frac{(2x+1)i\pi}{2N}\right] COS\left[\frac{(2y+1)j\pi}{2N}\right] \quad (1)$$

where $i, j = 0, 1, 2, \ldots, N-1$, and $C(k) = \begin{cases} \frac{1}{\sqrt{2}} & if\ k = 0 \\ 1 & if\ k > 0 \end{cases}$

In the implementation of this function, simple table lookups can replace several terms of the equation to simplify the DCT algorithm and improve its computation efficiency. For example, the two cosine terms only need to be calculated once and stored for later use. Likewise, the C(x) terms can also be replaced with table lookups. [Lossy Data Compression JPEG, 2017]

DCT compression algorithm [Cabeen and Gent, 2010]:

1. Divide the original image into blocks of size 8 x 8;
2. Pixel values of a gray-scale image range from 0-255 but DCT is designed to work on pixel values ranging from -128 to 127. Therefore each block is modified to work in that range;
3. Calculate the DCT matrix using Equation (1);
4. Apply DCT to each block;
5. Compress each block through quantization;
6. Entropy encode the quantized matrix.

The Proposed Grayscale Images Compression Algorithms

In this section, we firstly present the known FIC algorithms for grayscale images using quadtree decomposition, and quadtree decomposition with Huffman coding technique. Then, we present two proposed hybrid FIC algorithms for grayscale images, using DCT with quadtree decomposition, and DCT with quadtree decomposition and Huffman coding technique.

FIC of Grayscale Images Using Quadtree Decomposition Algorithm: The steps of this algorithm are as follows:

Algorithm 1 (Grayscale Quadtree)

Begin

1. Read a grayscale image;
2. Resize the image to 128x128;
3. Apply quadtree encoding technique;
   - 3.1 Divide the resized image using quadtree decomposition with threshold value between 0 and 1, and minimum and maximum dimensions equal 2 and 64, respectively;
   - 3.2 Record x and y coordinates and size of the blocks resulted from the quadtree decomposition step;
   - 3.3 Find mean value of each block values;
4. Calculate the Compression Ratio (CR);
5. Decode the data using quadtree decoding;
6. Reconstruct the image;
7. Calculate PSNR between the original image and the reconstructed image.

End.

FIC of Grayscale Images Using Quadtree decomposition with Huffman Coding Algorithm: The steps of this algorithm are as follows:

Algorithm 2 (Grayscale Quadtree-Huffman)

Begin

1. Read a grayscale image;
2. Resize the image to 128x128;
3. Apply Quadtree encoding technique (Step 3 of Algorithm 1) on the resized image;

4. Apply Huffman encoding technique:
   - 4.1 Calculate probabilities of frequencies of occurrence of the image blocks;
   - 4.2 Create Huffman dictionary corresponding to the blocks probabilities;
   - 4.3 Encode the data using Huffman encoding algorithm;
5. Calculate the CR;
6. Decode the data using Huffman decoding algorithm;
7. Reconstruct the image.
8. Calculate PSNR between the original image and the reconstructed image.

End.

Proposed FIC of Grayscale Images using DCT and Quadtree decomposition Algorithm: The steps of this algorithm are as follows:

Algorithm 3 (Grayscale DCT-Quadtree)

Begin

1. Read a grayscale image;
2. Resize the image to 128x128;
3. Apply the DCT compression algorithm on the resized image;
   - 3.1 Partition the image into non-overlapping blocks, then apply the DCT to each block;
   - 3.2 Quantize the DCT coefficients of each block of the image;
4. Apply quadtree encoding technique (Step 3 of Algorithm 1) on the resultant image;
5. Calculate the CR;
6. Decode the data using Quadtree decoding;
7. Reconstruct the image;
8. Calculate PSNR between the original image and the reconstructed image.

End.

Proposed FIC of Grayscale Images using DCT and Quadtree decomposition with Huffman Coding Algorithm: The steps of this algorithm are as follows:

Algorithm 4 (Grayscale DCT-Quadtree-Huffman)

Begin

1. Read a grayscale image;
2. Resize the image to 128x128;
3. Apply the DCT compression algorithm (Step 3 of Algorithm 3) on the resized image;
4. Apply Quadtree encoding technique (Step 3 of Algorithm 1) on the resultant image;
5. Apply Huffman encoding and decoding technique (Step 4-8 of Algorithm 2).

End.

The Proposed RGB Images Compression Algorithms

Although the algorithms presented above are for grayscale images, RGB images are compressed following the same algorithms. Since the RGB image is composed of three components, red, green, and blue, it is treated as though it were three separate images, each of a different color component, and each image would be compressed separately.

In this section, we present four proposed hybrid FIC compression methods for RGB images, using (1) quadtree decomposition, (2) quadtree decomposition with Huffman coding technique, (3) DCT with quadtree decomposition, and (4) DCT with quadtree decomposition and Huffman coding technique.

Proposed FIC of RGB Images Using Quadtree Decomposition Algorithm: The steps of this algorithm are as follows:

Algorithm 5 (RGB Quadtree)

Begin

1. Read a RGB image;
2. Resize the image to 128x128;
3. Set the threshold values (between 0 and 1) for red, green and blue components of the image;

4. Apply quadtree encoding technique:
   - 4.1 Divide resized image using quadtree decomposition;
   - 4.2 Record x and y coordinates and size of the R, G and B blocks resulted from the quadtree decomposition step;
   - 4.3 Find mean value of the values in each R, G and B block;
5. Calculate the CR;
6. Decode the data using quadtree decoding;
7. Reconstruct the RGB image:
   - 7.1 Reconstruct the R component of the image;
   - 7.2 Reconstruct the B component of the image;
   - 7.3 Reconstruct the G component of the image;
   - 7.4 Reconstruct the image from its R, G, and B components;
8. Calculate the PSNR between the original image and the reconstructed image.

End.

Proposed FIC of RGB Images Using Quadtree decomposition with Huffman Coding Algorithm: The steps of this algorithm are as follows:

Algorithm 7 (RGB Quadtree-Huffman)

Begin

1. Read a RGB image;
2. Resize the image to 128x128;
3. Apply quadtree encoding technique (Steps 3 and 4 of Algorithm 5) on the resized RGB image;
4. Apply Huffman encoding technique (Step 4 of Algorithm 2);
5. Calculate the CR;
6. Decode the data using Huffman decoding algorithm;
7. Reconstruct the RGB image (Step 7 of Algorithm 5);
8. Calculate the PSNR between the original image and the reconstructed image.

End.

Proposed FIC of RGB Images using DCT and Quadtree decomposition Algorithm: The steps of this algorithm are as follows:

Algorithm 6 (RGB DCT-Quadtree)

Begin

1. Read a RGB image;
2. Resize the image to 128x128;
3. Apply the DCT compression algorithm on the resized RGB image:
   - 3.1 Partition the image into non-overlapping R, G and B blocks, then apply the DCT to each block;
   - 3.2 Quantize the DCT coefficients of each block of the image;
4. Apply quadtree encoding technique (Steps 3 and 4 of Algorithm 5) on the resultant RGB image;
5. Apply Steps 5-8 of Algorithm 5 to reconstruct the RGB image.

End.

Proposed FIC of RGB Images using DCT with Quadtree decomposition and Huffman Coding Algorithm: The steps of this algorithm are as follows:

Algorithm 8 (RGB DCT-Quadtree-Huffman)

Begin

1. Read a RGB image;
2. Resize the image to 128x128;
3. Apply the DCT compression algorithm on the resized RGB image (Step 3 of Algorithm 7);
4. Apply quadtree encoding technique (Steps 3 and 4 of Algorithm 5) on the resultant RGB image;
5. Apply Huffman encoding and decoding technique (Step 4-8 of Algorithm 6).

End.

Experimental Results

This section presents the results of two sets of experiments that we have conducted to evaluate the effectiveness of the presented hybrid compression algorithms, for grayscale and RGB images, which combine the DCT with the quadtree decomposition method and Huffman coding technique.

The algorithms are implemented using MATLAB 7, on MacBook Pro, Intel Core i5, 2.3GHz. The performance of the presented image compression techniques is evaluated by measuring the quadtree decomposition time, the decompression time, the PSNR, and the compression ratio.

Peak Signal-to-Noise Ratio (PSNR) is defined as the ratio between the maximum possible power of a signal and the power of corrupting noise that affects the fidelity of its representation [Wikipedia, 2016]. PSNR is most commonly used to measure the reconstruction quality of lossy image compression. The signal in this case is the original data, and the noise is the error introduced by compression. When comparing compression codecs, PSNR is an approximation to human perception of reconstruction quality. Higher the value of PSNR, better the quality of the reconstructed image The PSNR (in dB) is defined, via the mean squared error (MSE), as:

$$PSNR = 10 \times log_{10}\left(\frac{MAX_I^2}{MSE}\right) \qquad (2)$$

where $\boldsymbol{MAX_I}$ is the maximum possible pixel value of the image, and ***MSE***, given a noise-free m×n image ***I*** and its noisy approximation ***K***, is defined as:

$$MSE = \frac{1}{m \times n}\sum_{i=0}^{m-1}\sum_{j=0}^{n-1}[I(i,j) - K(i,j)]^2 \qquad (3)$$

Image Compression Ratio (CR) determines the efficiency of the compression algorithm. It is defined as the ratio between the size of the original image and the size of compressed image:

CR = Size of original image / Size of compressed image

Grayscale Images Experiments

In the first set of experiments, we have applied the presented four hybrid FIC algorithms for grayscale images (Quadtree, Quadtree-Huffman, proposed DCT-Quadtree, and proposed DCT-Quadtree-Huffman) to Lena and Camera Man images. The images are resized to 128x128. Figure 1 shows the original images and the decompressed images after applying each of the four algorithms, with two different threshold values: 0.5 and 0.1. The quadtree decomposition and decompression times (in seconds), the PSNR values, and the compression ratios obtained for the two grayscale images, by using the four algorithms, with the two threshold values, are shown in Table 1, and graphically represented in Figures 2 to 5, respectively. It can be seen from the table and the figures that:

- The effect of using different threshold values: for both images, when using different threshold values with each method, the compression ratios are not affected; when using Quadtree and Quadtree-Huffman with the smaller threshold value (0.1), the PSNR values are improved; but when using the proposed algorithms: DCT-Quadtree and DCT-Quadtree-Huffman, the PSNR values are same for both threshold values. The Quadtree decomposition time and the decompression time were better when using the four algorithms with the larger threshold value (0.5).
- The quadtree decomposition time: for both images, with threshold value 0.5, all algorithms have taken same quadtree decomposition time; but with threshold value 0.1, for Lana image, Quadtree, Quadtree-Huffman, and proposed DCT-Quadtree algorithms have taken less decomposition time than proposed DCT-Quadtree-Huffman algorithm, and for Camera Man image, Quadtree-Huffman and proposed DCT-Quadtree-Huffman algorithms have taken less decomposition time than the other two algorithms.
- The decompression time: for both images, with both threshold values, the proposed DCT-Quadtree, the proposed DCT-Quadtree-Huffman, and Quadtree-Huffman algorithms, respectively, have taken less decompression time than the Quadtree. These results indicate that combining Quadtree with any or all of the other 2 methods reduced the decompression time.
- The PSNR values: for both images, with the two threshold values, the proposed algorithms, DCT-Quadtree and DCT-Quadtree-Huffman, have higher PSNR values than the Quadtree-Huffman and Quadtree algorithms. These results indicate that the combination of DCT with Quadtree and with Quadtree-Huffman has improved the quality of the reconstructed images.
- The compression ratio: for both images, with the two threshold values, the proposed algorithms, DCT-Quadtree and DCT-Quadtree-Huffman, have higher CR than the Quadtree and Quadtree-Huffman algorithms. These results indicate that the combination of DCT with Quadtree and with Quadtree-Huffman has enhanced the CR.

Original Image	Lena 		Camera Man 	
Threshold	**0.5**	**0.1**	**0.5**	**0.1**
Quadtree				
DCT-Quadtree				
Quadtree-Huffman				
DCT-Quadtree-Huffman				

Figure 1. The results of applying the four hybrid FIC algorithms to two grayscale images

Table 1. The results of applying the four hybrid FIC algorithms for grayscale images with two thresholds

		Lena		Camera Man	
Threshold		**0.5**	**0.1**	**0.5**	**0.1**
Quadtree Decomposition Time (Seconds)	**Quadtree**	0.007	0.009	0.008	0.08
	DCT-Quadtree	0.007	0.009	0.008	0.08
	Quadtree-Huffman	0.007	0.009	0.008	0.008
	DCT-Quadtree-Huffman	0.007	0.015	0.008	0.016
Decompression Time (Seconds)	**Quadtree**	0.016	0.085	0.023	0.098
	DCT-Quadtree	0.005	0.076	0.006	0.082
	Quadtree-Huffman	0.013	0.063	0.018	0.078
	DCT-Quadtree-Huffman	0.01	0.047	0.015	0.048
PSNR	**Quadtree**	21.33	22.35	19.60	22.16
	DCT-Quadtree	22.63	22.63	22.3	22.3
	Quadtree-Huffman	20.333	22.55	19.65	22.26
	DCT-Quadtree-Huffman	22.63	22.63	22.3	22.3
CR	**Quadtree**	16.0	16.0	4.0	4.0
	DCT-Quadtree	17.0	17.0	5.0	5.0
	Quadtree-Huffman	16.0	16.0	4.0	4.0
	DCT-Quadtree-Huffman	17.0	17.0	5.0	5.0

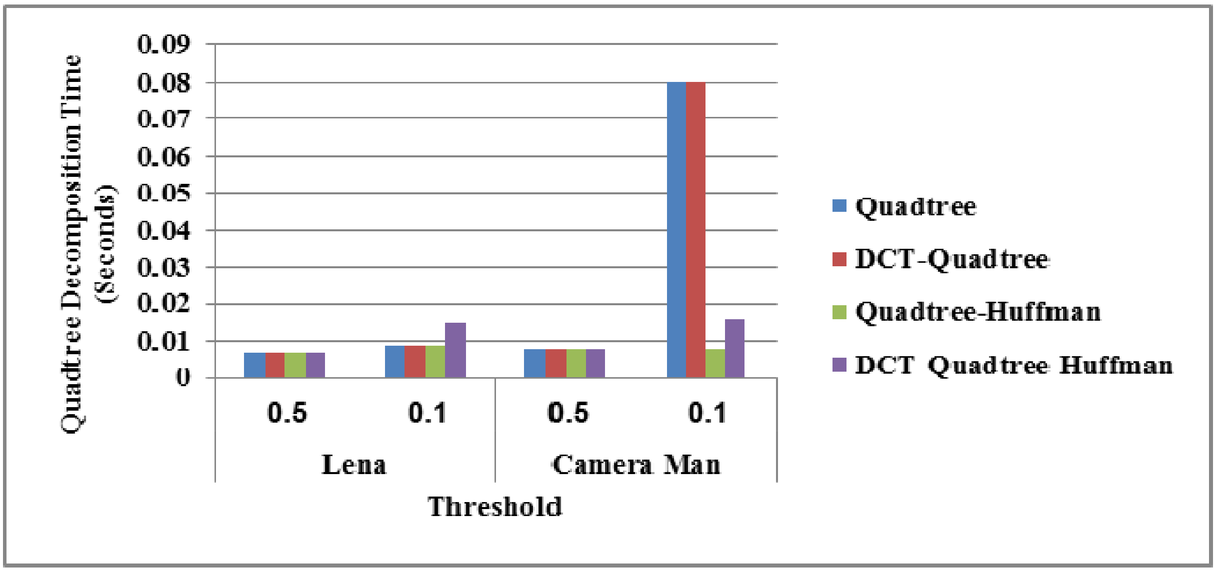


Figure 2. A comparison between the quadtree decomposition time for the four hybrid FIC algorithms for grayscale images with two different thresholds

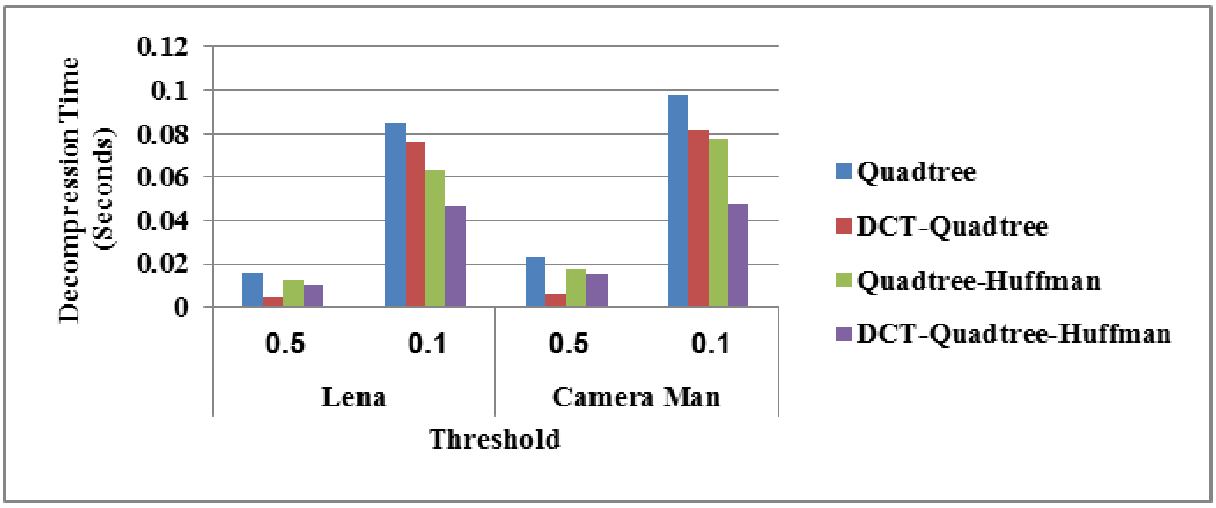


Figure 3. A comparison between the decompression time for the four hybrid FIC algorithms for grayscale images with two different thresholds

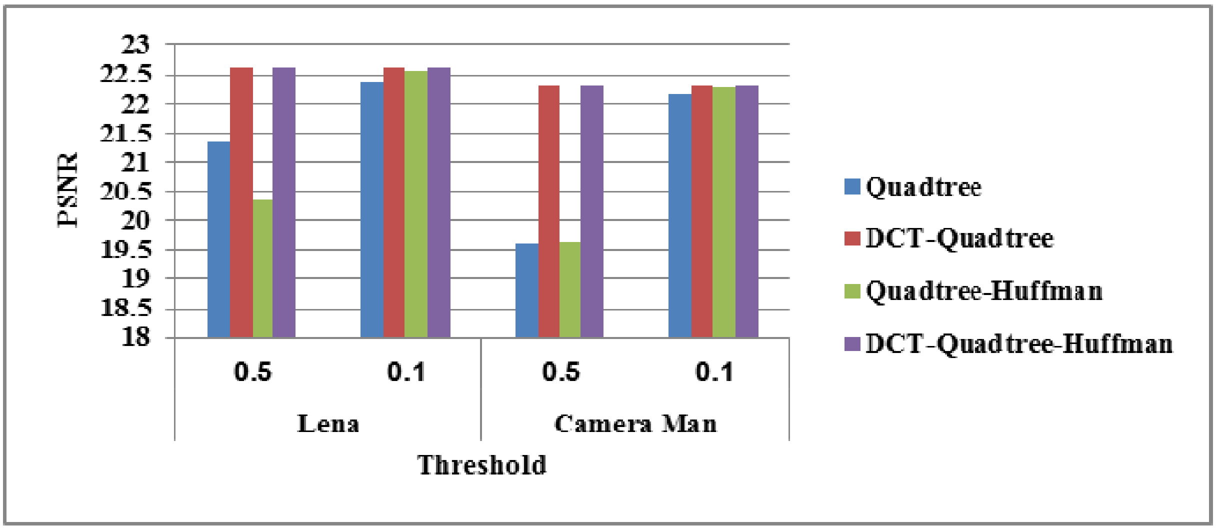


Figure 4. A comparison between the PSNR values for the four hybrid FIC algorithms for grayscale images with two different thresholds

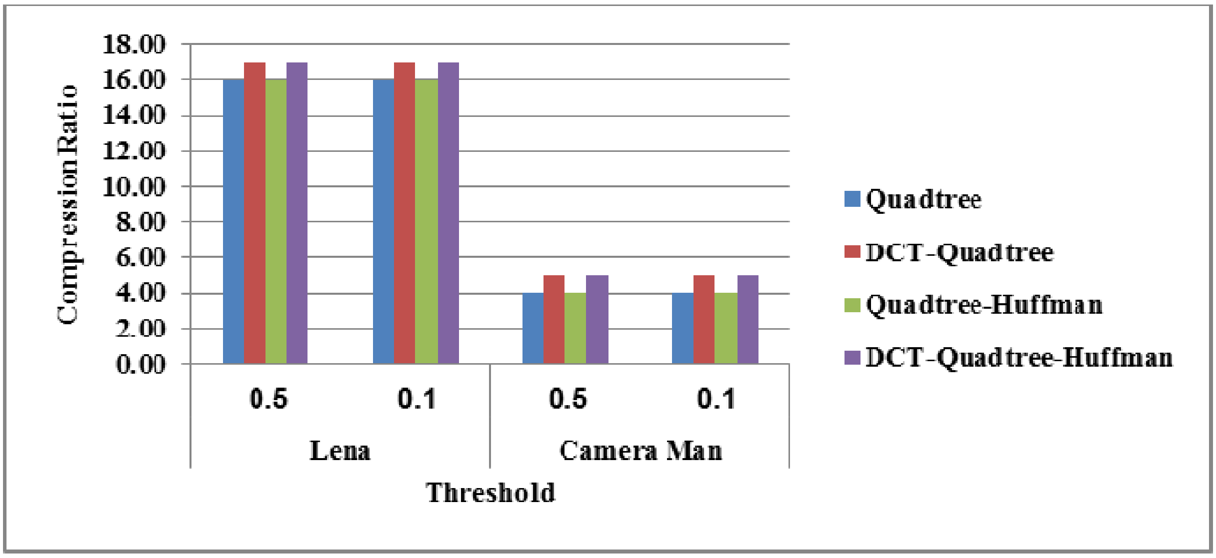


Figure 5. A comparison between the compression ratio for the four hybrid FIC algorithms for grayscale images with two different thresholds

RGB Images Experiments

In the second set of experiments, we have applied the four proposed hybrid FIC algorithms for RGB images: (Quadtree, DCT-Quadtree, Quadtree-Huffman, and hybrid DCT-Quadtree-Huffman) to Lena and Ship images. The images are resized to 128x128. Figure 6 shows the original images and the decompressed images after applying each of the four algorithms, with two different sets of threshold values: [0.5, 0.5, 0.5] and [0.1, 0.1, 0.1] for red, green and blue components of the RGB image.

The quadtree decomposition and decompression times (in seconds), the PSNR values, and the compression ratios obtained for the two RGB images, by using the four algorithms, with the two sets of threshold values, are shown in Table 2, and graphically represented in Figures 7 to 10, respectively. It can be seen from the table and the figures that:

- The effect of using different threshold values: for both images, when using different threshold values with each method, the compression ratios are not affected; when using the smaller set of threshold values, [0.1, 0.1, 0.1], with the four algorithms, the PSNR values have improved; but the quadtree decomposition time and the decompression time were better when using the larger set of threshold values [0.5, 0.5, 0.5] with the four algorithms.
- The quadtree decomposition time: for the two images, with the two sets of threshold values, on average, the DCT-Quadtree and DCT-Quadtree-Huffman have taken less decomposition time than the other two algorithms. These results indicate that combining Quadtree and Quadtree-Huffman with DCT reduced the decompression time.
- The decompression time: for both images, with the two sets of threshold values, the DCT-Quadtree-Huffman, Quadtree-Huffman, and DCT-Quadtree have taken less decompression time than the Quadtree algorithm. It can be seen also that DCT-Quadtree has taken less decompression time than Quadtree, and DCT-Quadtree-Huffman has taken less time than Quadtree-Huffman, which means DCT caused reduction in the decompression time.
- The PSNR values: for both images, with the two sets of threshold values, the DCT-Quadtree and DCT-Quadtree-Huffman have higher PSNR values than the Quadtree and hybrid Quadtree-Huffman algorithms. These results indicate that the combination of DCT with Quadtree and with Quadtree-Huffman has improved the quality of the reconstructed images.
- The compression ratio: for both images, with the two sets of threshold values, the DCT-Quadtree and DCT-Quadtree-Huffman have higher CR than the Quadtree and hybrid Quadtree-Huffman algorithms. These results indicate that the combination of DCT with Quadtree and with Quadtree-Huffman has enhanced the CR.

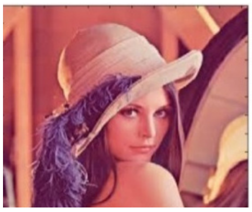
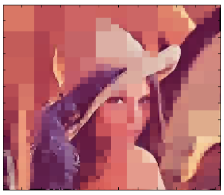
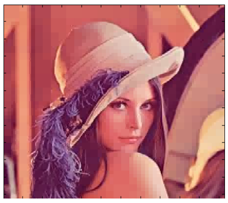
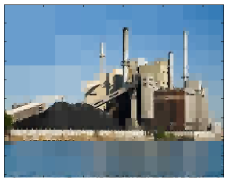
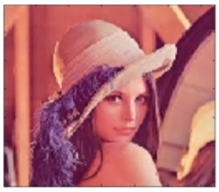
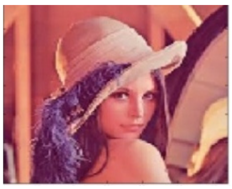
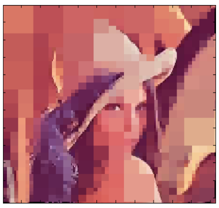
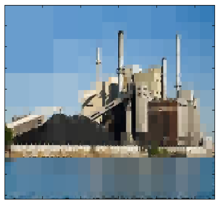
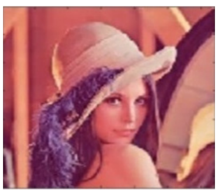
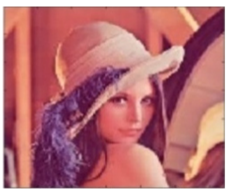
Original Image	Lena 		Ship 	
Threshold	[0.5,0.5,0.5]	[0.1,0.1,0.1]	[0.5,0.5,0.5]	[0.1,0.1,0.1]
Quadtree				
DCT-Quadtree				
Quadtree-Huffman				
DCT-Quadtree-Huffman				

Figure 6. The results of applying the four hybrid FIC algorithms to two RGB images

Table 2. The results of applying the four FIC algorithms to two RGB images, with two sets of thresholds

		Lena		Ship	
Threshold		0.5,0.5,0.5	0.1,0.1,0.1	0.5,0.5,0.5	0.1,0.1,0.1
Quadtree Decomposition Time (Seconds)	Quadtree	2.136	11.635	3.192	12.883
	DCT-Quadtree	2.102	2.131	2.134	2.171
	Quadtree-Huffman	2.136	11.371	3.089	12.592
	DCT-Quadtree-Huffman	2.172	2.295	2.109	2.388
Decompression Time (Seconds)	Quadtree	0.020	0.066	0.044	0.085
	DCT-Quadtree	0.014	0.061	0.034	0.063
	Quadtree-Huffman	0.016	0.059	0.026	0.065
	DCT-Quadtree-Huffman	0.013	0.052	0.023	0.065
PSNR	Quadtree	51.42	82.73	55.25	83.73
	DCT-Quadtree	87.52	88.35	82.63	83.64
	Quadtree-Huffman	51.42	82.73	55.25	83.73
	DCT-Quadtree-Huffman	87.52	88.35	82.63	83.64
CR	Quadtree	2.61	2.61	1.53	1.53
	DCT-Quadtree	3.09	3.09	3.072	3.072
	Quadtree-Huffman	2.94	2.94	1.88	1.88
	DCT-Quadtree-Huffman	3.09	3.09	3.072	3.072

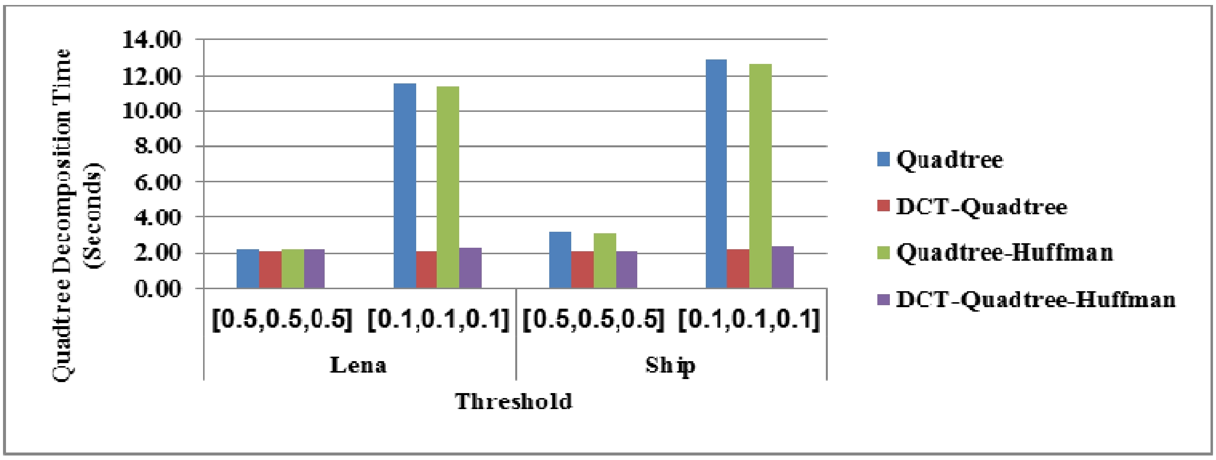


Figure 7. A comparison between the quadtree decomposition time for the four hybrid FIC algorithms for RGB images with two different sets of thresholds

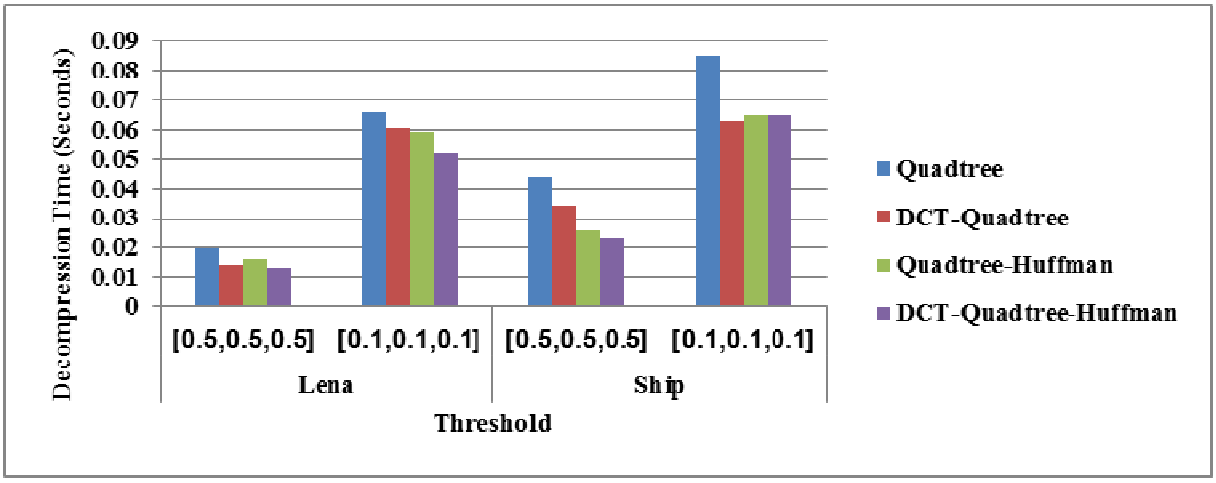


Figure 8. A comparison between the decompression time for the four hybrid FIC algorithms for RGB images with two different sets of thresholds

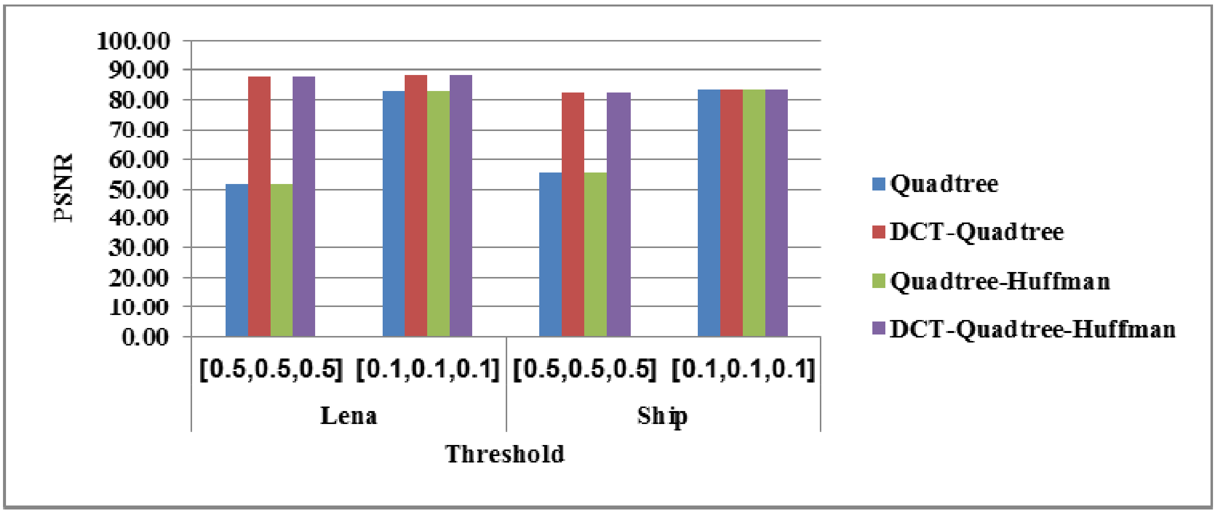


Figure 9. A comparison between the PSNR values for the four hybrid FIC algorithms for RGB images with two different sets of thresholds

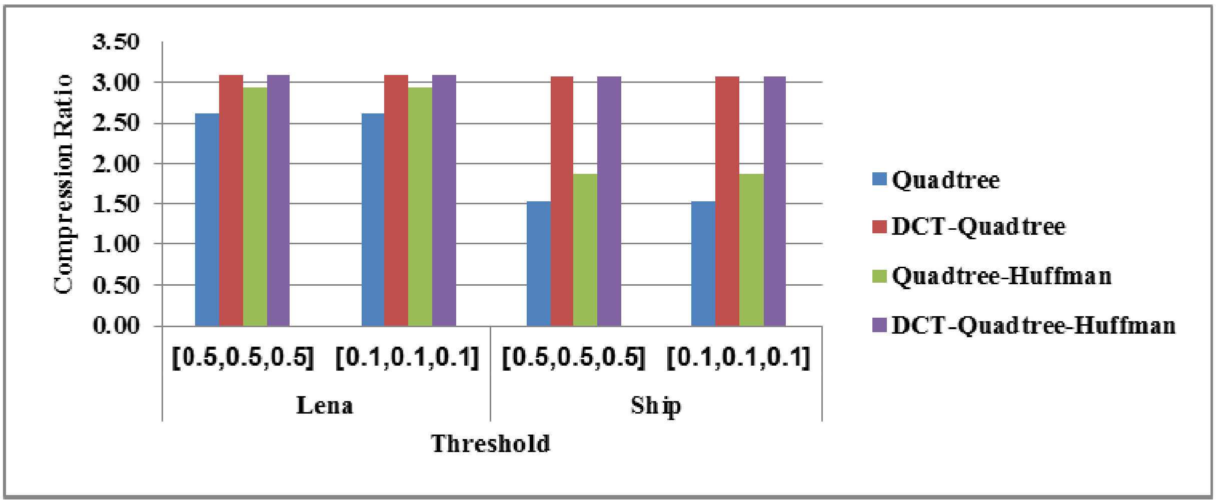


Figure 10. A comparison between the compression ratio for the four hybrid FIC algorithms for RGB images with two different sets of thresholds

Conclusion

This paper presented a set of hybrid FIC methods, for grayscale and RGB images, that combine the DCT and the Quadtree decomposition method with Huffman coding technique. The Quadtree decomposition method is used for the reduction of the search space and Huffman coding is used for improving the compression quality. The DCT is combined with the Quadtree decomposition and Huffman coding to improve the compression ratio. The presented hybrid FIC algorithms are: Quadtree, DCT-Quadtree, Quadtree-Huffman, and DCT-Quadtree-Huffman, for grayscale and RGB images.

Experiments have been conducted to evaluate the effectiveness of the presented hybrid compression algorithms. The results of these experiments indicated that the combination of DCT with Quadtree and with Quadtree-Huffman has improved the quality of the reconstructed images and enhanced the compression ratio, for both grayscale and RGB images. Also, the results indicated that, for grayscale images, combining Quadtree with any or all the other 2 methods reduced the decompression time; and for RGB images, combining Quadtree and Quadtree-Huffman with DCT reduced the decomposition and decompression times.

The presented FIC algorithms are applied to still images. As a future work, we intend to apply them to images in video sequences. In addition, we intend to apply the presented algorithms to images of color spaces other than RGB.

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HOW DOES THE AI UNDERSTAND WHAT’S GOING ON

Dimiter Dobrev

***Abstract**: Most researchers regard Artificial Intelligence (AI) as a static function without memory. This is one of the few articles where AI is seen as a device with memory. When we have memory, we can ask ourselves: “Where am I?”, and “What is going on?” When we have no memory, we have to assume that we are always in the same place and that the world is always in the same state.*

***Keywords**: Artificial Intelligence, Machine Learning, Reinforcement Learning, Partial Observability.*

***ITHEA Keywords**: I.2.6 Learning*

Introduction

The standard approach in Artificial Intelligence (AI) is to take a set of positive examples and a set of negative examples. We seek for a function that says “YES” for the positive examples given, and “NO” for the negative examples given. Using the function found, we begin to predict the right answer for examples which we do not know whether are positive or negative.

In essence, the standard approach in AI represents an approximation. What is sought for is an approximation function. It is usually sought for in a given set of functions. For example, in neural networks, the function is sought for in the set of neural networks.

As a typical example of the standard approach to AI we can indicate [1] where a static function covering certain positive and negative examples is sought. In articles like [2], things are a bit different, because there are new examples at every step and at each step the approximation function changes. However, in [2] we are again seeking for a static function without memory, although at each step this function is different. In [2] the idea is that we constantly improve the approximation function, but at each specific moment we have one specific static function.

The only research in which AI is seen as a memory device is the research related to Reinforcement Learning. Even in this area there are two main branches called “Partial Observability” and “Full Observability”. Do we need memory when we see everything? Of course not! If we see the current state of the world, we do not need to remember anything from the past because everything we need to know is encoded in what we see. That is, the only branch of AI where AI is considered as a memory device is the Reinforcement Learning with Partial Observability. This article refers exactly to this branch of Computer Science.

Why are we saying that such articles are few? There are many articles in the field of Reinforcement Learning, but they are largely devoted to the Full Observability case, for example [3, 4]. When referring to Partial Observability, it is usually said that there is such an option, but it is not said what we are doing in this case.

In this article we ask the question “What is going on?” If you translate this question in terms of Reinforcement Learning, it will sound like this: “What is the state of the world, we are in at the moment?” If you look at the states of the world as a graph, the question “What is going on?” can be translated as “Where are we? In which vertex of the graph are we in?” If we think of the real world, “What is going on?” means “What is our physical location at the moment and what is the state of the world at this moment?”

To say in what state of the world we are, we must first describe the states of the world. It will never be easy, because we do not see these states completely, but only partially (Partial Observability). For this reason, the description of the states of the world is related to imagining something invisible.

For this purpose we will introduce the concept of “property of the world”, representing a set of states of the world. With this concept we will describe the current state of the world. This will happen by the properties of the world that we know are valid or not. In this way, we will determine that the current state is an element of the intersection of a group of sets, i.e. an intersection between properties that are valid at this moment and the complements of the properties that are not valid. If these properties are enough, then the intersection of all these sets will be small enough and the description of the current state of the world will be precise enough. (That is, we do not define the current states with precision to one single state but with precision to a set of states.)

To describe the properties of the world, we will first see what properties we have. All we have are the experimental properties. We will want to describe particular property through what we have. This will happen by stating that from a given experimental property it follows something for the property we are describing. For example, that it follows that the property is true with some probability. The good cases are when it follows that it is true with a 100% probability, or vice versa – it is false to a 100%.

How will we determine the properties? To form a drop of rain we need a speck of dust that serve as a condensation nucleus. Similarly, in order to create a property that is defined for all the states of the world, we need to have the property defined for a relatively small subset. Based on this subset we will make an extrapolation and assume that the probability for the whole set is the same as for this subset.

Who are these condensation nuclei by which we will obtain the required properties of the world? These will be the tests defined in [8] and the corresponding function of the test.

This article is, in its essence, a continuation of [8], but readers shouldn't have necessarily read [8] to grasp the idea of the present article. (Short versions of [8] have been published in [9] and [10]). In [8] the term "Testable state" describes five different things: tests, function of the test, prediction of the function, test property, and test state. Those five different things denoted by a single term can be considered a mistake, though between the first and second there is a bijection. The prediction is also determined completely provided that we've specified the moment it is for (i.e. after how many steps). As to the test property, it is a continuation of the function of the test. This function can be continued in many ways, but we are looking for a continuation that is as natural as possible. The test state depends on the splitting into groups of relative stability. This splitting can be done in many ways, but the meaningful splittings are few.

This article begins with the introduction of three new definitions of Reinforcement Learning and proof of the equivalence of these new definitions with the standard definition. The aim of the new definitions is to help us introduce the concepts of chance, test state and noise. We will give a specific example that justifies the introduction of the new definitions. We will introduce the concepts of event (experiment), we will say what a property of the world is and we will consider the properties defined by experiments. We will introduce the term of test. From it we get the test property. When we have not one, but many groups of relative stability, then instead of a test property we will talk about test state. That means that we will talk about is a test that defines not one, but several properties of the world. Finally, we say how to define theories that describe the properties of the world.

Thus we will answer the question "What is going on at the moment?" The answer is a set of properties so that we know whether they are valid at the moment. The next action of our device will not depend solely on what it sees at the moment. It will also depend on what properties of the world are currently valid (that is, on what is going on at the moment). This means that our device will be a device with memory.

Formulation of the problem

We have a sequence: *action, observation, action, observation ...*, and we want to understand this sequence. Our goal is to predict how this sequence will continue and to choose such actions to achieve the best possible outcome. We will assume that this sequence is not accidental, but that it is determined by the rules of a world in which we are.

The representation of the world is essential because we will try to understand the world, that is, we will try to build a model, and we will seek for this model in a form close to the form we’ve chosen.

We will look at four possible definitions of the type of world. We will prove that these four definitions are equivalent. The benefit of the three new definitions we will offer is that they will help us in building a model of the world. The second definition will help us add the notion of chance to our model, the third definition will naturally lead us to the notion of Testable Property, and the fourth definition will give us the possibility to add the notion of noise.

Definition 1. This is the usual definition of the world in Reinforcement Learning. It is the following: We have a set *S* of the internal states of the world and one of them, s_0, is the initial one. How the internal state of the world changes is determined by the function *World*, and what we see at each step is determined by the function *View*. The following applies:

$$s_{i+1} = World(s_i, a_{i+1})$$
$$v_i = View(s_i)$$

Here, actions and observations (a_i and v_i) are vectors of scalars with dimensions *n* and *m,* respectively. Each of these scalars will be a finite function with *k* possible values, where *k* is different for the different coordinates of *a* and *v*.

Let’s ask whether the function *World* is single-valued or multivalued. By this definition this function is single-valued, that is, the world is determined. With the new definitions this will change.

The next question is whether the function *World* is total or partial. In [8] we argued that we should assume that *World* is a partial function and that cases in which it is not defined will be assumed to be incorrect moves. Again in [8] we have accepted that at each step we will be able to check for each move whether it is correct or incorrect. That is, at each step we will see two things. First, we’ll see what the function *View* returns, and second, we’ll see which actions are correct and which are incorrect at this moment.

As we have said, this is the usual definition used by most authors (for example [3, 4]), except that other authors usually assume that the function *World* is total and that all moves are correct. We will not prove that the definitions in the case of total and partial function *World* are equivalent because they are not. In the case in which we allow incorrect moves the device gets more information. This can be partially emulated in the case in which there are no incorrect moves, but this emulation will be only partial.

Definition 2. With the single-valued function *World* we lack the concept of chance. Let’s see how we can add it. If we allow *World* to be multivalued, then the next state of the world will not be definite but will be one of several possible. Okay, but we’d like to say something about the probabilities of these different options. Let's have *k* different options. Let each of them happen with some probability p_i. (Now things look like the Markov Decision Process or, in particular, the Partially Observable Markov Decision Process, because here we are dealing with the Partial Observability case.)

So, we can define chance in two possible ways. With the first one the probability is not determined at all, and with the second one it is determined too precisely. Both options are not what we want, so we will choose something in the middle. In the first possible way, the probability is somewhere in the interval *[0, 1].* In the second way, the probability has a fixed value *p* (i.e. it is in the interval *[p, p]).* In the variant which we will choose the probability will be in an interval *[a, b].* That is, we will not know the exact probability, but we will know that the probability is at least *a* and less than *b.*

There are two kinds of chance – predictable chance and unpredictable chance. If you roll a dice, the probability of rolling a six is 1/6. This is a predictable chance. When we ask our boss for a salary increase, the answer will be 'YES' or 'NO', but we can not say how likely it will be 'YES'. This is an unpredictable chance. The predictable chance is quite determined because, thanks to the Law of Large Numbers, we know quite well how many the successful attempts will be. The option we chose is a combination of predictable and unpredictable chance. Of course, in order for the definition to be correct, we must ensure that some inequalities are fulfilled. If *World (s,a)* has *k* possible values of probabilities in the intervals $[a_i, b_i]$, the following inequalities must be fulfilled:

$$a_i \leq b_i \qquad \sum_{i=1}^{k} a_i \leq 1 \qquad \sum_{i=1}^{k} b_i \geq 1$$

If $Sum = \sum_{i=1}^{k} a_i$

Then the following inequalities must also be fulfilled:

$$b_i \leq 1 - Sum + a_i \qquad (1)$$

We will assume that inequality (1) is equality for at least one *i.* We can assume even that it is equality for at least two *i.*

By this, the second definition of the world is complete. We only have to prove that it is equivalent to the first one.

Note: We will assume that the function *World* will not be too indeterminate because it would make the world too incomprehensible. For example, supposing that from any state and upon every action, the function *World* with the same probability can move to any other state, this will make the world completely incomprehensible. It would be much more understandable if, in most cases, the function

World returns a single possibility, and when the possibility is not only one, the possibilities are few and one is much more likely than the others.

Theorem 1. The second definition is equivalent to the first.

Note: The next proof is technical, so we advise the reader to skip it and take it on trust.

Proof: One of the directions is easy, because it is obvious that the first definition is a special case of the second. For the opposite direction, it is necessary for an arbitrary world described in the second definition to build a world equivalent to that described in the first definition.

The idea of the proof is to hide the probability in a natural number. We will have a function *F,* which will calculate the next number from the current random number. Similarly, the pseudo-random numbers in computers are calculated. There, starting from one number (we will start from zero), each subsequent pseudo-random number is obtained by the function *F* from the previous one (i.e. *F (x)).* Function *F* must be sufficiently complex so that we could not guess the next number. Furthermore, *F* must be good, which means that for one particular *Q* all remainders of modulus *Q* are equally probable.

In our case we have two chances and that is why we will add two natural numbers and two functions (*F_good* and *F_bad*). We will like these two functions to be complex enough (noncomputable and not allowing any approximation with a computable function). We will also want the sequence $F^{i}(0)$ to be without repetition for both functions. Only function *F_good* is to be good for a particular Q, but for *F_bad* we will not want anything more. We will use *F_good* to calculate the predictable chance, and *F_bad* to calculate the unpredictable one.

We will define the function *F_good* as follows:

F_good(0)=0

$F\_good^{\,i+1}(0)$*= the first unused number of those which give a remainder k on the division by Q, where* $k \in [0, Q-1]$ *is selected randomly.*

Note: We've defined the function *F_good* through an endless process in which at each step we are making a random choice (for example, pulling balls out of a hat in which there are *Q* balls). In this way we get an noncomputable function. In this article we try to describe a specific algorithm and everything that is part of this algorithm must be computable. The functions *F_good F_bad* are not part of this algorithm. Their task is only to show the equivalence of two definitions. We only need to show that these two functions exist. We will never build these functions in practice nor calculate them.

Note: If for some reason we want to realize the functions *F_good* and *F_bad,* (for example, if we want to build an artificial world in which to test AI), we would use the standard function *Random,* which is embedded in most programming languages. Unlike *F_good, Random* is not perfect, but it's good enough for practical purposes. *Random* does not work with natural numbers but with a 32-bit integer. It is not perfect in the sense that it is complex, but it is not infinitely complex and the next random number can theoretically be guessed (but in practice it cannot). Moreover, the sequence of random numbers is not infinite, but repeats (but after a rather long period). That is, for practical purposes *F_good* can be replaced with *Random. F_bad* can also be built using *Random.* We only have to take care of what the function returns. All classes by module *Q* not to be equally probable but to have another probability distribution. From time to time, this probability distribution to change randomly.

After this preparation we are ready to prove the equivalence of the two definitions. Let us have a world according to the second definition, respectively, *S*, s_0, and *World.* The new world, which we will build, will have a set of the states S×ℕ×ℕ, initial state $(s_0, 0, 0)$, and function *Big_World,* which is defined as follows:

Big_World((s, x, y), a)= (s', F_good ^{2}*(x), F_bad(y))*

Here *F_good* is square because this function is used twice in the calculation of *s'.*

s'= World(s, a), when *World (s, a)* has one possible value

When *World(s, a)* has *k* possible values, we select one of them as follows:

We divide the interval *[0, 1]* to *k+1* subintervals with lengths from a_1 to a_k, and the last one with a length of the remainder. We choose a random point in the interval *[0, 1].* If the point has fallen in some of the first *k* subintervals, *s'* will be equal to the i^{th} of the possible values of *World (s, a).* Here *i* is the number of the interval in which we have fallen in.

If the point has fallen in the last subinterval, we calculate the coefficients:

$$c_i = \frac{b_i - a_i}{1 - \text{Sum}}$$

We once again take the interval *[0, 1]* and mark the points c_i in it. Thus we divide the interval *[0, 1]* into *k+1* subintervals (some with zero length). We once again select a random point in the interval *[0, 1]* and see in what subinterval it has fallen in. The first subinterval corresponds to *k* possible values of the *World (s, a),* the second corresponds to *k-1* ones*,* and the last corresponds to 0 possible values. We cannot fall in the last interval because it is with length zero (because we assumed that at least one of the inequalities (1) is equality). We can even assume that the last two intervals are zero. Once we understand how many and what are the possible values of *World (s, a)*, we choose one of them with unpredictable chance. How does this work? If the possible values are *R,* we take the number *(y mod R)+1.* If this number is 1, we take the first of the options, if it is 2, we take the second, and so on.

We didn't say how we choose a random point in the interval *[0, 1].* For this purpose, we divide the interval *Q* into equal parts. We take the number *(x mod Q)+1* and this will be the number of the interval which we will choose. It does not matter which of the points of this interval we will take because these intervals will be entirely contained in the intervals we look at. For the latter to be true, we will assume the following:

We assume that the numbers *a* and *b* are rational (if irrational, we can make them rational with a small rounding). We will even assume that these numbers are of the type *x/100* (i.e., that they are hundredths). If they are not, we can again make them of the type with a small rounding. (In this case the rounding is acceptable because we are talking about an interval of probability and if the difference is small, it will be felt only after a very large number of steps.) We will further assume that the number *Q,* which we used in the construction of *F_good*, is equal to the least common multiple of the numbers from 1 to 100.

Note: At the first selection of a random point we take the number *(x mod Q)+1,* and for the second selection instead of *x* we take *F_good (x),* i.e. we take the next random number.

Thus the equivalence of the first and second definitions is proven. ■

Definition 3. The following idea stands behind this definition: What we see can be changed without changing the place where we are. For example, you are in the kitchen and you see that it is painted yellow. The next day you're back in the kitchen, but this time you see it is painted blue.

We will change the function *View* and the states of the world. If the function *View* returns a vector of scalars of dimension *m,* then we will add *m* visible variables to each state. Now the finction *View* will return the values of these *m* variables. Apart from the visible variables, we will also add a *u* number of invisible variables. The idea of invisible variables is that not everything can be seen. For example, if someone is angry with you, you do not see it, but it does matter because it will later affect his actions.

We will introduce the concept of cumulative state and it will consist of the state of the world and the value of all the $|S|.(m+u)$ variables. When we want to emphasize that this is not a cumulative state, we will say a standard state.

The function *World* will be defined for the tuple <cumulative state, action> and will return a cumulative state. Again, the function *World* will be multi-valued and will not be total. That is, again, we will allow chance and incorrect moves.

Note: A variable can not be bonded with the state to which it is attached. This is especially true for invisible variables. We are asking ourselves whether we should introduce global variables. The answer is that global variables are not needed because every local variable can be considered to be the same for a whole set of states and even for all states.

Note: We will assume that the values of the variables will not change too violently because that would make the world too incomprehensible. For example, supposing that the function *World* of each step changes the value of all variables in an absolutely arbitrary way, it would produce a completely incomprehensible world. It would be more comprehensible if most of the variables are constants and do not change, and when they are no constants – to change relatively rarely and according to clear and simple rules.

Theorem 2. The third definition is equivalent to the second one.

Proof: To prove the equivalence of the second and third definition is easy. If we assume that all variables are constants (i.e., the function *World* never changes them), we will see that Definition 2 is a partial case of Definition 3, and vice versa, if we look at the cumulative states as standard states, then from the third definition we get the second. The only remark is that variables can be infinitely many (if the states are infinitely many). From there, we get that cumulative states may be too many (continuum), but if we limit ourselves to the achievable states, they will still be finitely or countably many. ■

Definition 4. The next thing we will do is introduce the notion of noise. We will change Definition 3 so that the new function *View* will no longer return the pure value of the visible variables but the value distorted with some noise. To describe the noise, we will need two things – volume and spectrum of the noise. The volume will be a number *Volume* in the range *[0, 1].* The spectrum of the noise will be a k-tuple $<p_1, ..., p_k>$. For each visible variable we will add more *k+1* invisible variables that will contain the volume and spectrum of the noise of this variable (i.e., we will add more *|S|.m.(k+1)* invisible variables, if *k* is the same for all visible variables). The function *View* will return the value of the visible variable with probability *1-Volume.* With probability *Volume* it will return noise, which will be one of the possible *k* values, each with a probability of the corresponding p_i.

Let the cumulative states in Definition 4 be the same as in Definition 3. That is, they will depend on all visible and invisible variables, but will not depend on what the function *View* returns. In other words, here function *View* is not completely determined by the values of the visible variables of the respective state, but also by the values of invisible variables that describe the noise. Also, some predictable chance takes part in the definition of the function.

Note: This is how we describe the situation in which at its input the device receives information distorted by some noise. What do we do when the output information is also distorted by noise? We've dealt with the second option in Definition 2 because there we've already introduced the possibility for the same action to have different possible consequences for the world, each one with a different probability.

Note: Again we are dealing with a type of Partially observable Markov decision process (POMDP) with the difference that in our case variables have their value, although it is distorted by noise, while with

POMDP there is only noise (i.e., for all visible variables the noise is 100% which means Volume = 1). The only thing that distinguished the various states in POMDP is that they have different noise spectra.

Note: We will assume that the world is not too noisy, because if everywhere the noise level is maximum (i.e. one) and everywhere the spectrum of the noise is the same, then such a world would be completely incomprehensible. It would be more comprehensible if the noise level is zero or close to zero.

Theorem 3. The fourth definition is equivalent to the third.

Proof: It is clear that Definition 3 is a special case of Definition 4. To every world of Definition 3 we can add noise whose level is zero everywhere and we will get a world equivalent to it by Definition 4.

Let’s do the opposite. Let’s take a world by Definition 4. For each of the cumulative states in this world we will see how many possible outputs the function *View* can return (in principle, the possible output is only one, but because of the noise we can have many possible outputs). For each of these possible outputs, we will make a new state in which the visible variables have exactly the value of the possible output.

Note: From every cumulative state we make many new standard states. What we will get will be a world by Definition 3 (and even by Definition 2 because the visible variables will be constants). But do we lose any information by this? Do we lose the value of the visible and invisible variables? No, because this information is coded in the new state we create. It reflects the value of all variables of all states (not just of the variables of the current standard state).

How will we define the function *World* of the new world? If between two cumulative states there is a connection when the action *action* takes place and there is a probability that this connection is likely to take place in the interval *[a, b],* then each of these two cumulative states has been replaced by many standard states and between each state from the left ones and each state from the right ones there will still be a connection when the action *action* takes place. The difference will be only in the probability interval. It won’t be *[a, b]* but *[a.p, b.p],* where *p* is the probability that it is exactly this output obtained on the right. That is, no matter what state you started from on the left, they all behave the same way because they are the same according to the future. They differ only in the present (function *View*) and they are distinct only because of the noise. ■

Example

We will give a specific example that will show us the benefits of Definitions 2, 3 and 4. The example will be similar to the one we gave in [6, 7]. The difference will be that here as an example we will use the chess game, whereas in [6, 7] we used the Tic-Tac-Toe game. The main differences are two:

1. In chess there are 64 squares, while Tic-Tac-Toe has only nine.

2. In chess we will give the commands “pick up the piece” and “put down the piece”, while in Tic-Tac -Toe instead of these two commands we have only “put a cross.”

Let’s have a world in which we play chess against an imaginary opponent. We will not see the whole board with all the pieces. Instead, we’ll see only one square and the piece on this square. Let us remind that here we are dealing with the case of Partial Observability. If we were able to see the whole board, we would deal with the case of Full Observability. However, seeing only one square will not be a problem, because we will be able to move our eyes, i.e. change the square we see and thus look around the entire chessboard.

Our action will be 3-tuple consisting of <horizontal, vertical, command> where:

- horizontal∈{Left, Right, Nothing}
- vertical∈{Up, Down, Nothing}
- command ∈{“pick up the piece”, “put down the piece”, New Game, Nothing}

The function *View* will return 3-tuple <chessman, color, immediate_reward>

- chessman∈{Pawn, Knight, Bishop, Rook, Queen, King, Nothing}
- color ∈{Black, White, Nothing}
- immediate_reward∈{-1, 0, 1, Nothing}

Our action will allow us to move our eyes on the chessboard – horizontally, vertically, and even diagonally (i.e. simultaneously horizontally and vertically). We will need patience, because we will move only one square per step.

In addition to being able to look around the board, we will need to be able to move the pieces. To do so, we have two commands: “pick up the piece”, i.e. pick up the piece you are looking at at the moment. The other command is “put down the piece”, i.e. drop the piece you picked up and put it on the square you looking at at the moment. Of course, you will not see which piece you picked up, but we hope you remember it.

For our convenience, we will assume that we always play with the white pieces and that when we move the piece (i.e., we put down the picked up figure) the imaginary opponent will immediately (exactly on the same step) make his move, i.e. on the next step one of the black pieces will be in another place. When the game ends, immediate_reward will be 1, -1 or 0, depending on whether we have won or lost, or the game has ended in a draw. In the rest of the cases immediate_ reward will be Nothing. We will assume that when the game ends, we will not start the next one immediately, but we will have time to look at the board and find out why we lost. When we are ready for the next game, we call the command “New Game” and the pieces are arranged for a new game.

Will there be wrong moves? Yes, when we are in the left column, we will not be able to move to the left. When we are looking at a black piece or an empty square we will not have the right to pick up a piece. If we have already picked up a figure, we will not have the right to pick up another one until we have put down the first one.

Let us describe this world in the terms of Definition 1. The set of the internal states will consist of three things (of 3-tuples). The first will be the position of the board (the possible positions are many), the second will be the coordinates of the eye (64 possibilities), the third will be the coordinates of the picked up piece (65 options – one extra for the case when we have not picked up anything). In order to make the things to be determined, we will assume that the imagined opponent is determined, i.e. at one and the same position he will always play the same move. (Most programs that play chess are determined opponent.) In this case, it is clear how to define the functions *World* and *View*.

What are we to do if we want the imagined opponent not to be determined? For example, it may be a person or even a group of people (who are changing and alternating to play against us). The person, and especially the group of people, is an undetermined opponent. It is natural that at certain position some moves are more probable and others less probable, but it is not possible to tell exactly what the probability of choosing a certain move is. In this case, Definition 2 is most natural.

The states of the world will still be the same, but the function *World* will now be multi-valued. If we want to go back to Definition 1 but preserve the indeterminacy of the imaginary opponent, we will have to make a complex construction of the type we did in the proof of Theorem 1. This would increase the number of internal states of the world. They are too many even now, but they are finitely many, while in the example above they will become infinitely many.

How would this example look like with Definition 3? In this case, the states will be only 64 (as many as the squares on the board.) Each state will have three visible variables (chessman, color, immediate _ reward). The third visible variable will be common for all 64 squares. The fact that the third variable is common to all squares is not said in any way. The device that tries to understand the world will have to detect this fact alone. Of course, this fact is not difficult to detect. Much more difficult to detect is the fact that the first two visible variables depend on the state of the world and are different for each square.

In this case, we will not be able to go only with the visible variables. We need somewhere to remember which piece we've picked up. This fact is not visible in any square. So we'll add an invisible variable to each square. When we pick up the piece, it will disappear from the visible variables and will appear in the invisible variable of the square from which we have picked it up.

Thus we've constructed a world with 64 states and four variables to each state (three visible and one invisible). The number of achievable cumulative states in the world under Definition 3 is just as much as the achievable states under Definition 2. However, the world with 64 states seems much simpler and more understandable, justifying the introduction of Definition 3.

Let us now present the world in the terms of Definition 4. There is no noise in this world and there is no point in presenting it by Definition 4. To make such a presentation necessary, let's add some noise.

We will assume that the white is very dark and the black is very bright and that it is likely to mess up the color of the piece. We will present this in the following way. To the visible variable "color" we will add noise with some volume and spectrum: 50% Black, 50% White, Nothing 0%. When the square is empty, we will assume that the noise is with *Volume=0.*

Next we will assume that the pieces Pawn and Bishop are very much alike and we may mess up them. To present this, we will add noise to the visible variable piece, which noise will have a non-zero value when the figure is a Pawn or a Bishop. For the other pieces let the noise be zero. The spectrum will be Pawn 50%, Bishop 50% and 0% for the other cases.

Now let's assume the King is too feminine and sometimes we mess up him with a Queen, but not the other way around, i.e. we never mess up the Queen with a King. We will present this by adding a little noise when the piece is a King with a spectrum: Queen on 100%.

Thus we saw that we can describe a rather complex world in a very comprehensive way. This example justifies the introduction of Definitions 2, 3 and 4.

Event or experiment

An event would be when something happened, and an experiment when we did something. Of course, for every event we may have tried to cause it or prevent it. Therefore, we believe that with every event we have some involvement. That's why we will not distinguish between an event and an experiment and will accept that these two words are synonymous.

We want to define the concept of experiment (event). To do this first we will say what history is and what local history around the moment q is.

Definition: History is the sequence of actions and observations $a_1, v_1, \ldots , a_{t-1}, v_{t-1}$, where t is the current moment.

Note: We will not tell in which world a given history has happened because we will assume that it is the world that we have to understand. It does not matter by what definition this world is defined because all four definitions are equivalent (we will use mostly Definitions 3 and 4 because they are most convenient to work with).

Note: What is one step from the history? Should it be <action, observation> or vice versa? We’ve decided it would be <action, observation> because the moment in which we are thinking is the moment before the action. We are not thinking in the moment after the action. In this moment we just wait for the observation to take place. For this reason, the history begins with a_1. Our device will have to make the first action blindly because it would still not have seen anything. So we can choose the first action randomly. We will choose it to be the vector of zeros (we will de

Note the zero by Nothing – see [6]). We have said that the world starts from s_0, but we do not see what happens in s_0. Therefore, the world begins actually from s_1.

Definition: Local history around the moment *q* is a subsequence obtained from a history, where from the number of each index we’ve subtracted *q*.

The representation of the local history is: $a_{-k}, v_{-k}, \ldots, a_0, v_0, \ldots, a_s, v_s$. We’ve obtained it from one particular history by taking the step a_q, v_q and adding the last *k* steps before it and the next *s* steps after it. Once we subtract *q* from the number of each index, step a_q, v_q becomes a_0, v_0.

We will look at the local history as a sequence of letters (that is, as a word). We will present this word as a concatenation of two words *past.future.* Here *past* ends with a_0, v_0, and the *future* is from there onwards. That is, the present is part of the past, because it has already happened.

We want to define the concept of experiment (event) as a Boolean function that is monotonous (that is, if the event has happened in one particular local history and if the local history is continued, it still would have happened). We also want this Boolean function to be computable.

Definition A: Experiment is a Boolean function defined on local histories *past.future,* which is defined by two decidable languages L_1 and L_2 and is true exactly when $\exists u_1, u_2$ such that $u_i \in L_i$ and u_1 is the end of *past* and u_2 is the beginning of the *future.*

Note: We shouldn’t necessarily become aware of the event at the moment it happens. We can become aware of it later (when it goes in the news). This is the reason why the event depends not only on past but also on the future. We might not need to be aware of the future and not even the entire past. That is, we can understand that the event will happen before it has happened (for example, a few steps before it happens).

In this definition of an event, we miss some events that we need to count from the day of birth. For example, the event “Today is Monday” is an event of this kind. If you do not want to miss these events, we will have to change our definition A as follows:

Definition B: The same as Definition A with the difference that you want local history to start from the beginning (from a_1, v_1) and u_1 will not only be an end of *past* but will be equal to *past.*

In [8] we discussed dependencies without memory (i.e. events, by Definition A, in which the lengths of u_1 and u_2 are restricted). In [8] we discussed the dependencies with memory (i.e. events, by Definition A, where L_1 and L_2 are regular languages.)

Note: Regular languages can be described as words starting with something, containing something, ending in something and in which something has happened *m mod n* times. Definition A tells us that *past* must end in something or contain something. Definition B adds the cases when *past* must begin with something and cases when something has happened *m mod n* times. However, we are not interested in cases when *past* begins with something or contains something. We are not interested in these cases because although we are theoretically looking at many possible histories, in fact, the history is just one (our history). This single history has either begun with something or not. In this history, something has either happened or has not happened. It would be interesting, if something happened recently (for example, no more than 3 steps ago). This would create an event that changes its value over time. Events that are constant are not interesting to us.

Experimental properties

Once we've said what an experiment is, we are ready to define experimental property. Let us first define property and local history around a state.

Definition: Property is a set of cumulative states of the world. At one particular moment, a property will be valid if the corresponding cumulative state is an element of the property (i.e., of the set of the cumulative states).

Note: In the Definitions 1 and 2 there is no difference between the standard and cumulative state. In this case, the property is simply a set of states.

Note: When we discuss property, we will usually mean not the set but its characteristic function. We will talk about partial properties (whose characteristic function is partial) and the continuation of the partial property to total.

Definition: Local history around the state s is a local history around a particular moment q, which is obtained from a history in which the corresponding state s_q is exactly the state s.

That is, local history around s is a history that tells us how we have gone through s.

Note: We can have many different histories around the state s because the past and the future are not defined unambiguously. The ambiguity of the future comes from the fact that we do not know which of the possible actions we will choose. In Definitions 2, 3 and 4 to this ambiguity we've added the ambiguity of chance. As for the past, it is also ambiguous as there may be many different states that after an action could lead to the state *s*. Of course, we can assume that each successive state is brand new. That is, assume that the states do not repeat themselves. However, we prefer to assume that there are no unnecessary states in our world (i.e., if two states are equivalent according to the future and to the present, we have merged these two states into one). That is, we will assume that the states can be repeated. Even cumulative states can be repeated, and standard ones are often repeated.

Each experiment defines one property in the following way:

Definition: Experimental property is the set of cumulative states *s*, such that for *s* there is a local history around *s*, such that in this local history the experiment has happened (i.e. the experiment was carried out in this local history).

Each experiment defines a property, but that property is not recognizable but semi-recognizable. That is, if the experiment is performed, the property is valid (at that moment). We can not say the opposite. If the experiment has not been performed, we can not say that the property is not valid because in another development of the past and the future maybe the experiment would be possible. If we have noise (Definition 4) then even the present may have another development because of the noise.

Each experiment divides the set of cumulative states into two parts (those that the experiment may be performed around and those for which this can not happen). When the experiment has been conducted around a cumulative state, this means that it is one of the states of the property. Not all states of the property are equally probable. Some are more probable, others are almost improbable. We can not say what the probability of the corresponding cumulative state is, but we hope that gathering statistics for a particular experiment will indirectly take account of these probabilities.

Experimental properties are the best we have. If we want to define a property, we will have to describe it through the experimental properties. This description will be made using the statistics we have collected. In [8] we saw how to collect statistics for dependencies without memory. Also in [8] we discussed even events with memory.

What is a test?

The drawback of experimental properties is that they are semi-recognizable. We want to add properties that are recognizable (they may not be recognizable at any moment, but there should be moments when we can say whether the property is valid or not).

For this purpose we will introduce the term "test".

Definition: Test is an experiment with a result. The result is a Boolean function that is defined always when the experiment has been performed and which does not depend on the way the experiment has been performed. We will call to the experiment the condition of the test.

The idea is, each time an experiment is conducted to have a result and this result to be "YES" or "NO". We do not want the result to depend on the past and the future, because there are many possible developments for the past and for the future. So let us assume that the result depends only on the present.

Present is what we see at the moment (the moment of interest, not the current moment because the current moment is one, but we are interested in all moments). That is, the present is v_q. We see this, but we see something more. We see which of the actions are correct at this moment and which are not. To the vector v_q we can add Boolean variables, one for each action. These variables will be visible. The value of each of them will tell us whether the action is correct at this moment.

Note: When writing a theoretical article we choose a structure that is easy to describe. This article is a practical one and therefore we will choose a structure, which is most suitable for realization. Therefore, instead of describing the possible moves, we will describe the cumulative of moves (see [8]). The idea is not to play with the individual moves, but to operate with whole sets of moves. We will see two Boolean variables for each cumulative move. This variable will tell *all* and *nobody.*

In [8] we've presented some arguments showing that we can assume that the result of the experiment has the form of x_i = *constant.* Here x_i is one of the visible variables and *constant* is one of the possible values of this variable.

Note: In [8] we decided that we will not necessarily try all possible moves in order to see which ones are correct. In the example we gave the possible moves are 36. If we try them all at each step, it would be annoying. Therefore, if the visible variable is one of those who we call *all* and *nobody,* then we will assume that the condition of the test guarantees that the necessary moves have been tried. If the value of the variable is true, then all the moves of the group should have been tried. If the value is false, then at least one move from the group must have been tried and it should be such a move that shows that the variable is not true.

Test functions

Each test determines one function on local histories.

Definition: Function of the test is the function defined in the moments in which the condition happened. The value of this function will be equal to the result of the test.

We want to continue the test function so that we have some prediction of the moments when it is not defined.

Definition: Theory of the test is a function that for each local history returns two numbers (prediction and confidence). We will assume that when the function of the test is defined, the theory returns the value of the function as a prediction with a confidence of one. In other cases, the confidence will be less than one.

The prediction is usually zero or one, but it may be between these two values. In this case, we have a prediction of the result with some probability.

Each test function defines a partial property. We will call it the smallest property of the test. The set in which this property is defined is the experimental property (here the experiment is the condition of the test). The value of the partial property is the value of the test result.

Note: The smallest property of the test is a generalization of the test function, because it is defined for particular moments for which the function is not defined.

Can we continue the smallest property of the test to a total property? Yes, we can, but we can do this in many different ways. The goal is to continue it in a natural way so that the resulting property actually describes the world.

Definition: Property of the test is each continuation for the smallest property of the test.

In [8] we discussed the example where the test is "Is the door locked?" At the moments when we've conducted the experiment, we know the answer. That is, we know the test function. We can correctly define what the correct answer would be for the states around which the test can be performed (although we will not know this answer, if we have not conducted the test). Is there a property of the world that describes the outcome of this test? Let us have the property "the door is locked" and let this property is changing by some rules. It seems like we only need to determine that property so we can predict the outcome of this test. In fact, in our world we may have many different doors and then it is not appropriate to describe the state of the world with just one property. Of course, we could say: "The door to which we are located is locked." This is a property that is always defined except when we are not to any door. However, a better description of the world would be if we introduce many properties (one for each door). So we come to the definition of a test state:

Definition: Let's assume we've split the set of cumulative states of the world into groups that we call groups of relative stability. The test state will be a Boolean function that is defined for each moment and for each of these groups.

Roughly speaking, the test state tells us which doors are locked and which doors are unlocked at the moment.

Definition: Theory of the test state is a function that for each local history and for each group of relative stability returns two numbers (prediction and confidence).

Note: We may have a group of relative stability in which the test is impossible. Then what to do? First possibility is to assume that the theory of the test state will give a prediction of this group with a confidence of zero. Second possibility is to make prediction anyway. Look at the open problem below.

How can we obtain the test theory from the theory of the test state? That is, how the fact that we have an idea about which doors are locked and which doors are unlocked will give us an idea of whether the door in front of us is locked? First, we need to answer the question of which door we are at (i.e., in which of the groups of relative stability we are in). Then we will take the prediction for this door that the theory of the test state gives us.

The groups of relative stability will be represented by the states of a finite automaton. If the finite automaton is deterministic, we will know exactly which group we are in. If not, we will know only approximately. If the automaton is deterministic, the test state can be expressed by several tests and the properties of these tests. The conditions of these tests will be the condition of the test plus the fact that we are in the corresponding state of the automaton. That's why we prefer the automaton to be deterministic. Otherwise, the condition that we are in the respective state of the automaton will not be a computable function.

Test states

We gave a formal definition of what a test state is. Let's say what the relationship between test states and Definition 3 is.

If the condition of the test is the universally valid condition, then the test states are exactly the visible variables. This is not entirely accurate, because the tests are Boolean and the visible variables have *k* possible values. To fix this inaccuracy, we will temporarily assume that the visible variables are also Boolean.

Let's have a test whose condition is the universally valid one and which returns the value of the first visible variable. Then the state of this test will be the first visible variable. Of course, this is not one variable because every standard state has its first visible variable. We are talking about many variables (perhaps even infinitely many). Many of these variables may be equal. They may even all be equal. Then the test state will not be composed of all of these variables. Instead of this we will take one variable from each group of equal variables.

That is, we have seen that if we have a world by Definition 3, its visible variables are test states. Let’s do the opposite. Let’s take the world by Definition 2 and a test whose result is the first visible variable. Let’s build a world by Definition 3, whose first visible variable is exactly the test state of this test.

For this purpose, we will split the states of the world into groups of relative stability. Which splitting are we to choose? Whichever we choose will do the job, but it is good to make the splitting so that it actually corresponds to the world and that the groups are really groups of relative stability.

Let us now assume that each group of relative stability is one standard state. We’ll add more invisible variables, if necessary, to store in them all the information we have about the cumulative state. We will define the functions *View* and *World* in a way that the resulting world is equivalent to the one from which we’ve started.

Note 1: We can represent a group of relative stability through several standard conditions. This splitting is useful, though not necessary. With this splitting the world can become much simpler. For example, instead of thinking that all permanently locked doors are in one standard state, it might be simpler if we have different states corresponding to different permanently locked doors.

What would happen if we choose an inappropriate splitting? Let us imagine that we have split the number of doors into metal and wooden ones. We assume that if one of the metal doors is locked, then all the metal doors are locked and likewise with the wooden doors. Then we see a locked metal door and we conclude that all metal doors are locked at the moment. The next moment we see an unlocked metal door. We decide that they are all unlocked now. Is it possible it really be so? It is possible and it cannot be confirmed or rejected experimentally. However, if the splitting is not adequate, the groups of relative stability will be very unstable.

Examples of test states

Let’s take the world we described in the example (the game of chess). Let’s suppose that the description of this world is by Definition 2. We will discuss two tests and see how through their test states the world can be split into groups of relative stability and thereby the world to be presented by Definition 3.

The first test will be “I see a white piece”. The condition of the test will be the universally valid condition (that is, when do I check whether I see a white piece. I always check.) The result of the test will be color=white.

What are the groups of relative stability? These will be the squares on the chessboard. The test property will be “There is a white piece in the square we are looking at”. The test state will be the position of the chessboard. Well, not exactly the position but that on which squares there is a white piece. The test state will not contain information about where the black pieces are or about which exactly is the white piece that is in the square.

We received a world with 64 standard states. The visible variables are clear. We need to add invisible variables in which to store the information about the cumulative state that has not stored in the visible variables. We can make this in the same way as we already did.

The second test will be "If I see a white piece, I can pick it up."

The result of the test will be "Pick up the piece is a correct move." We should

Note that "pick up the piece" is not a single move, but a whole group of moves (i.e. a cumulative move) because by picking up the piece we can simultaneously move horizontally or vertically. That is, the result of the test is "In the group of moves <*, *, pick up the piece> There is at least one correct move." We cannot have all moves of the group to be correct, because a move may be incorrect because of the movement (for example, if we are in the left column and try to move to the left). This group has a visible variable *nobody,* which has to be *false*. Formally, it will look like this: *nobody(<*, *,* "*pick up the piece*">*)=false.* Here is given for which cumulative move *nobody* is, because different cumulative moves have different variables *nobody.*

The condition of the test will be "I see a white piece" (i.e., color=white). We must add to the condition of the test that we have tried the moves from the group. If *nobody* is *true*, we've tried all the moves, if *nobody* is *false*, we've tried at least one move, but such one which is correct.

Here the groups of relative stability are two: states for which the test will always return *true*, and those for which it will always return *false*. We will have *false* when we've picked up another piece and have not put it down yet and when the game is over and we have not played "New Game" yet in order to begin a new one.

How will we present the world by Definition 3? As

Noted in

Note 1, a group of relative stability can be represented by more than one standard state. Here we will present the group in which the test always returns *false* by two standard states (when we picked up a piece and when the game is over). Let's

Note that there is no way to pick up a piece if the game is over.

We got a world with three standard states. The visible variables are clear. We need to add invisible variables in which to store all the information for the cumulative state. In other words, we need to store the position of the chessboard (for this we will need 64 variables or 2.64 if we are wasteful). We also need to store the coordinates of the square that we are looking at, and if we’ve picked up a piece – where we’ve picked it up from, and which this piece it is.

How do we find the theories?

What is the difference between the theory of the test and the theory of the test state? In the first case we assume that we have only one group of relative stability and that the test determines one property. In the second case, we assume that we have many groups of relative stability and that our test determines many properties of the world (one for each group).

We will describe how we determine the theory of the test. (The theory of the test state is determined in an analogous way.)

We have collected statistics for specific experiments. When both the experiment and the test are performed, we count how many times the test has returned “YES” and how many times it has returned “NO”. Let these be the numbers *n* and *m*. Then the prediction given by this experiment is $\frac{n}{n+m}$, and the confidence depends on *n*+*m*. At some point, many experiments have been conducted, each of which gives us some kind of prediction with some confidence. Here we will not discuss how to calculate the overall prediction and overall confidence.

Note: When a test state is distorted with noise (Definition 4), then we can not find rules that give an exact prediction (i.e. the prediction to be an integer). Each prediction, which is with a large enough certainty, will be approximate (i.e. it will be some probability *p* such that $0<p<1$). Conversely, if the prediction is approximate, there is no way to know if it’s because the result of the test is distorted by noise or because the condition of the test is such that it gives a rough prediction. If all predictions are approximate, we may assume that we have some noise or that we have not yet found a rule which will give us an exact prediction.

Besides experiments, we will predict the property of the test based on the assumption that this property is stable. We will assume that we have gathered statistics on how stable this property is. Based on this, we will assume that once we have checked the property (we have done the test), the value of the property is still the same for some time. The confidence of this assumption will decrease over time (i.e., the more steps goes after the test, the less we count on the assumption that the value is the same).

The next level is to make the assumption that we are not alone in the world. That there are other agents in the world and that this agents change the test state at their own discretion (see [8]).

How do we define groups of relative stability to define a test state that is meaningful and adequate. Once again we will use statistics. In fact, this is the task of finding a finite automaton that can meaningfully split the states of the world into groups. This task will also remain outside of the topics discussed in this article.

Open question: Sometimes the test property can not be tested. There are two such cases. The first is when a test property does not make sense. The second case is when it makes sense, but we can not test it directly, and therefore we must assess its value indirectly. The question is how to distinguish these two cases? For example, "Our house burnt down" and the case "My hands are tied". In the first case the test property "The door is unlocked" does not make any sense. In the second case the property makes sense, but we can not test it directly because our hands are tied. We can assess the property indirectly by using a rule of the type "Today is Monday, and on Monday the door is always unlocked". That would be a proper reasoning in the second case but not in the first.

Conclusion

This article began with the claim to be different and offer for AI something more than an approximation. However, here again the approximation method is used. When we have a test function and we want to continue it to a test property, then what we do in practice is an approximation. However, there are differences. Most authors search for an approximating function that should be the solution (i.e. it must be AI). Here we seek not one but many approximating functions (one for each property). These functions are not the AI. Their only task is to assist the device to understand what is going on at the moment.

Note: So to speak, if we had Full Observability and if we were able to see everything, these approximations would not have been needed at all. Although the search for test properties is directed to the case of Partial Observability, it would be helpful for us even in the case of Full Observability. The problem with Full Observability is that in this case we have too much information and it is very difficult to distinguish the essential from the inessential. Let's forget what we see and focus only on test properties that we have found. We will choose these test properties that are interesting and this will be the essential information that we will need.

As we have said, the approximation is not the whole solution, but only part of the solution. Before that, we need to collect statistics to have the basis on which to approximate. Here we should mention dependencies with and without memory, which we've discussed in [8]. Then we make an approximation based on the experiments and the statistics we have collected about them. We also use the assumption for the stability of the test states (this can also be regarded as an approximation). The next method we use to determine the value of test states is the assumption that there are other agents in the same world apart from us and that they are changing these test states in order to help us or screw us. This approach can no longer be called approximation, at least because there is no formula to compute it by. That is, the description in this article is more than just an algorithm for approximation.

Even after finding the test states the problem is not yet solved, because what remains is to plan the future actions to obtain maximum rewards.

Note: Here we set the task to describe a particular algorithm and it is the algorithm of the thinking machine. We are not asking ourselves what AI is or the question what the definition of AI is. These questions were discussed in [5] as well as in other earlier articles. That's why in [5] we use the classic definition of Reinforcement Learning, while in this article we have offered three equivalent definitions. When we want to give a theoretical definition of AI, then the classic definition of Reinforcement Learning us enough, but when we want to describe AI in sufficient detail to bring it to a realization, then we need to change the definition so that it is easier to work with it.

Why test properties and test states are so important? It is these properties and these states that give us the understanding of the world. To understand the world means to have an idea for things we do not see directly. For example, let's know that the door on the third floor is unlocked. In order to formulate this proposition, we need the respective test. In order to decide whether this proposition is true, we will need a theory of the test state of this test.

Many researchers in the field of AI agree that AI should be able to make logical conclusions based on a system of automated theorem proving – for example, propositional or predicate calculus. We also share this view, but the question is how from the sequence (action, observation) to reach propositional or predicate calculus. To have a propositional calculus we need propositions. To make a predicate calculus, we will need predicates. If we cannot understand the sequence (action, observation) it would be just a noise for us. How can we make propositions and predicates from this sequence? The binding unit we need is test properties and test states. For example, the test property "The door is unlocked" may be the proposition we are looking for. The test state "Door X is unlocked" will be the predicate from which we can make statements of the type "All doors are unlocked."

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APPLICATION OF BIOSENSORS FOR PLANTS MONITORING

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Abstract: *Current methods of diagnostics of plant state need to conduct expensive and long-time physical-chemical and microbial analyses of soil and plant samples. The chlorophyll fluorescence induction method allows determining the functional state of plant in express mode without plant damage and it gives an opportunity to estimate the influence of stress factors on the plant state. In recent decades a number of researches of the chlorophyll fluorescence induction were significantly increased because of appearance of relatively inexpensive portable fluorometers. This paper represents results of testing biosensors developed at the V.M. Glushkov institute of Cybernetics of NAS of Ukraine on base of chlorophyll fluorescence induction method. It were developed appropriate software to facilitate data acquisition and processing. Analysis of some experimental results by means of neural networks is discussed.*

Keywords*: fluorometer, biosensor, wireless sensor network, chlorophyll fluorescence induction, neural network, information technology.*

ACM Classification Keywords: *H.4 Information system application*

Introduction

Over the past decade portable devices of "Floratest" family were developed and manufactured in V.M. Glushkov Institute of Cybernetics of NAS of Ukraine. The researchers of chlorophyll fluorescence induction (CFI) effect encounter the problem to gain sufficient amount of data by means of autonomous fluorometers. Besides, the time of a measurement of chlorophyll fluorescence induction varies from several minutes to one hour, depending on environmental conditions, species of plants and experiment specificity. The temperature and humidity of air and soil, illuminance can vary, that can influence on reliability of measuring data. All this has to be taken into account during ecological and agro-ecological monitoring. So, to overcome above-mentioned disadvantages, it was designed wireless biosensors that are combined in wireless sensor network together with special network coordinators, and concentrator [Palagin at al, 2017]. The biosensors were tested in laboratory and field conditions. This paper represents some important results of that testing and data analysis.

Work objectives

Work objectives are testing of developed biosensors and developing database, software and methods to facilitate acquisition and processing of measured data.

Measurement of CFI and its parameters

The technique of laboratory or field experiment includes next:

1. Selecting plants. Planning and choosing testing plants. Goal of an experiment has to be taken into consideration when experiment is planned and plants are selected. A chosen plant-indicator has to be sensitive to stress factor [Guo and Tan, 2015].

2. Plants are grown in identical conditions in pots or on field with identical soil.

3. The grown plants are divided into few groups – control and experimental.

4. Experimental plants are put on influence of stressful factors of different degree in accordance with testing program.

5. Network of biosensors measures chlorophyll fluorescence induction (CFI) of control and experimental plants in accordance with testing program for type of stress and its degree in scheduled terms.

The using of few fluorometers or the developed network of wireless biosensors allows reducing the time needed for measurements and it can provide data that are more adequate. The time can be calculated according to formula:

$$t_e = \frac{\sum_i^N (t_{ad} + t_m + t_{pr})}{N_s},$$

where t_e is a time to get experimental data; N is an amount of measurements; t_{ad} is a time of dark adaptation of leaf; t_{pr} is a time needed to prepare the next measurement; t_m is a time of measurement of chlorophyll fluorescence induction curve, N_s is a number of sensors.

If the sensors are placed on a leaf under sunlight then the dark adaptation has to be not less than 20 minutes. If the plant (or its leaf) is placed during long period in a shadow then 5 minutes is enough for the dark adaptation.

6. Measuring data of chlorophyll fluorescence induction, acquires by biosensors from control and experimental plants.

7. It is useful to record the air and soil temperature and humidity during a measurement of chlorophyll fluorescence induction. In addition, chemical and biological analysis of soil can be used for specific

biological researches. It is allows to take into consideration climatic effect as additional stress factor on parameters of chlorophyll fluorescence induction.

8. The results of measurements are processed by means of graphical, statistical and correlation analysis and machine learning technique. Before analysis, the measured data can be normalized.

9. The finish result of testing is detecting the sensibility of biosensors to influence of different stresses.

Typical curve of chlorophyll fluorescence induction is shown on figure 1. For analysis of measured curves the researchers typically analyze special parameters of CFI curves such as: F_o (initial level of chlorophyll fluorescence); F_m (maximum level of chlorophyll fluorescence); F_{st} (stationary level of chlorophyll fluorescence); $F_v = F_m - F_o$ (variable fluorescence); Fv/Fm ratio, Area (the area above the fluorescence curve between F_o and F_m), F_j (fluorescence value at point J, t ≈ 2 ms); F_i (fluorescence value at I, t ≈ 30 ms) and so on. Also the machine learning method is getting popular recent years [Kalaji at al, 2017].

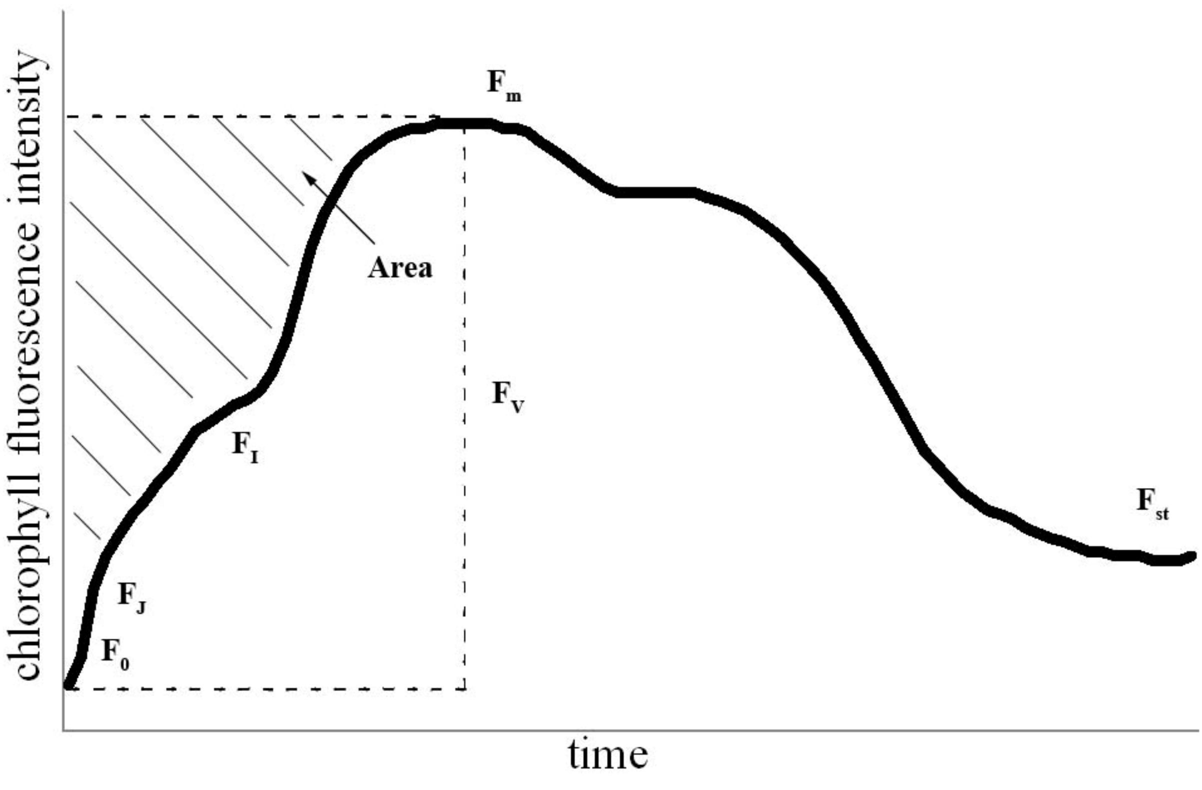

Figure 1. The typical curve of chlorophyll fluorescence induction

Development of software and database for work with chlorophyll fluorescence induction curves

Several activities have to be repeated during processing chlorophyll fluorescence induction curves (CFI) by means of personal computer: opening file with measuring results, graph building for previous visual estimation of dynamics of CFI curve, grouping different measurements, calculation of curves parameters and so on. It gets a lot of time. The special software FAnalyzer was developed to simplify the processing of chlorophyll fluorescence induction curves.

Functions of the developed software are the following:

1) receiving measuring data from biosensors and further data output in form of a graph.

2) storing the received measuring data on hard disk and opening in form of graphs;

3) opening and storing several curves of CFI in one file. The file can be opened later and processed by means of program packages such as R, Excel, Matlab and so on.

4) calculation and storing CFI curves parameters, that are frequently used to analyze the measuring results (F_m, F_o, F_{st}, Rfd, Area, F_i, F_j and other), and main statistical indicators for that parameters.

The graphical user interface of program is shown on figure 2.

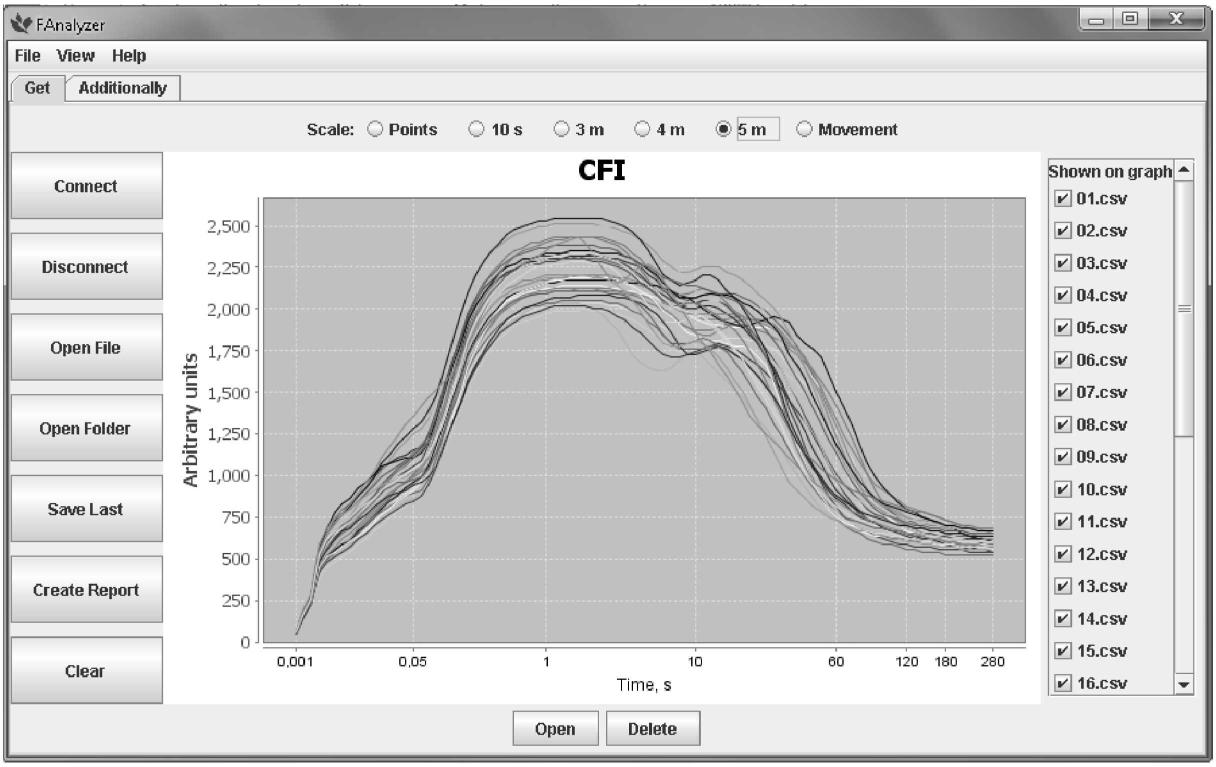

Figure 2. Graphical user interface

The suggested software allows to reduce time for preparing data to analysis, to calculate main parameters of CFI and proper statistical indicators. The calculation can be used for comparative analysis of plant states in conditions of influence of stress factors and in normal conditions.

During using multiple biosensors simultaneously it is necessary to store, process and visualize a large amount of measuring data. For convenience of users, the database and proper graphical user interface were developed. They allow storing a large amount of measurements in one place for further data analysis of measuring data by means of tools and methods, selected by user. During the database development, a set of entities was defined to represent in the database. The last ones contain information about: plant information; type of monitoring of plant state; measured curve of chlorophyll fluorescence induction; information about soil, air and parts of plant (in case of chemical-biological analysis);information about devices and sensors, used for measurements; weather information; information about a person, conducting measurements; information about an organization and a location, where measurement was conducted.

A database management system MySQL was used for database implementation. The database diagram is shown on figure 3.

Importing data to the database can be carried by means of special software.

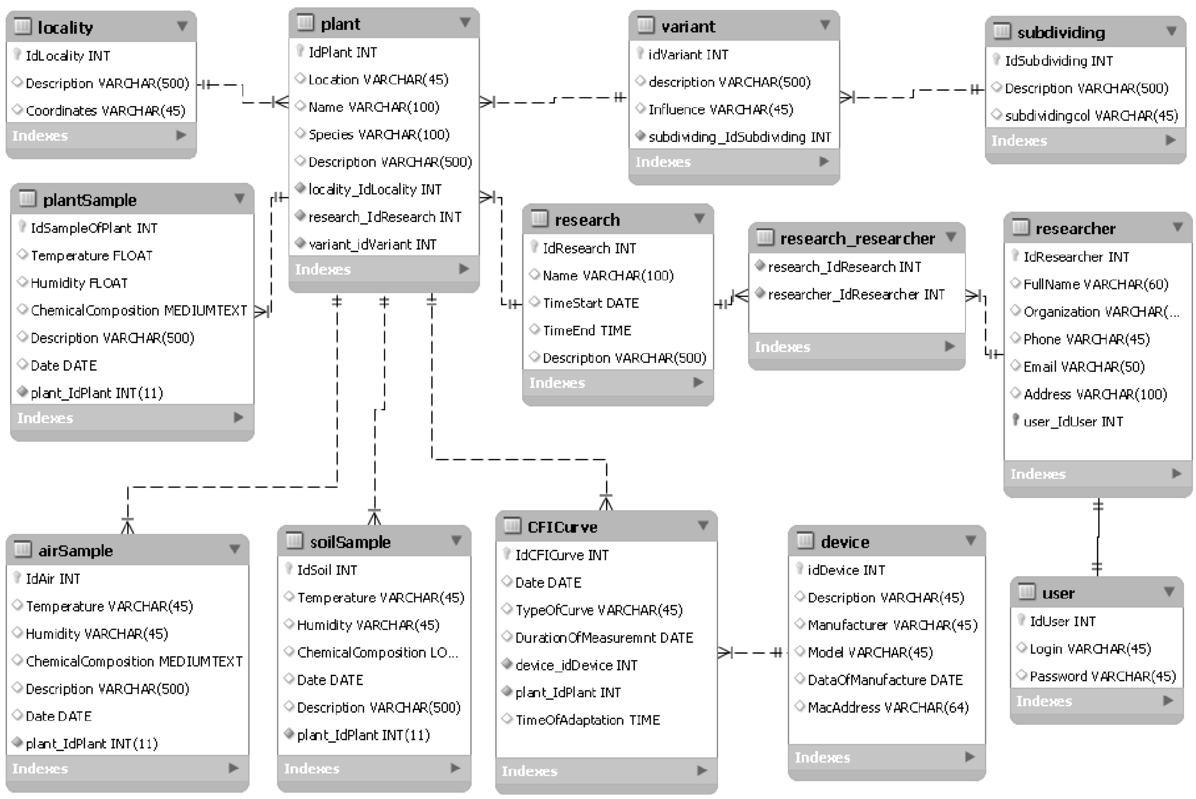

Figure 3. The database diagram

Research of change of chlorophyll fluorescence induction under influence of copper

To research the influence of heavy metals on plants it is reasonable to select the goose-foot plant. Goose-foot has a wide natural habitat, grows in a different environmental conditions. It was studied the influence of different doses of toxicant, copper sulphate ($CuSO_4$), on the test plants Plants were cultivated in 12 pots, three-four plants per pot. The plants were divided into 4 groups. Different concentration of $CuSO_4$ were dissolved in water and brought into the soil of these four groups.

Group 1 (V1) – control group without $CuSO_4$.

Group 2 (V2) – 1 g of CuSO4 / 1 kg of soil.

Group 3 (V3) – 3 g of CuSO4 / 1 kg of soil.

Group 4 (V4) – 6 g of $CuSO_4$ / 1 kg of soil.

The experiment was conducted during 13 days. At the beginning of the experiment the chlorophyll fluorescence induction was measured in all groups of plants (figure 4). The same day the water solution of CuSO4 was brought into soil of test plants.

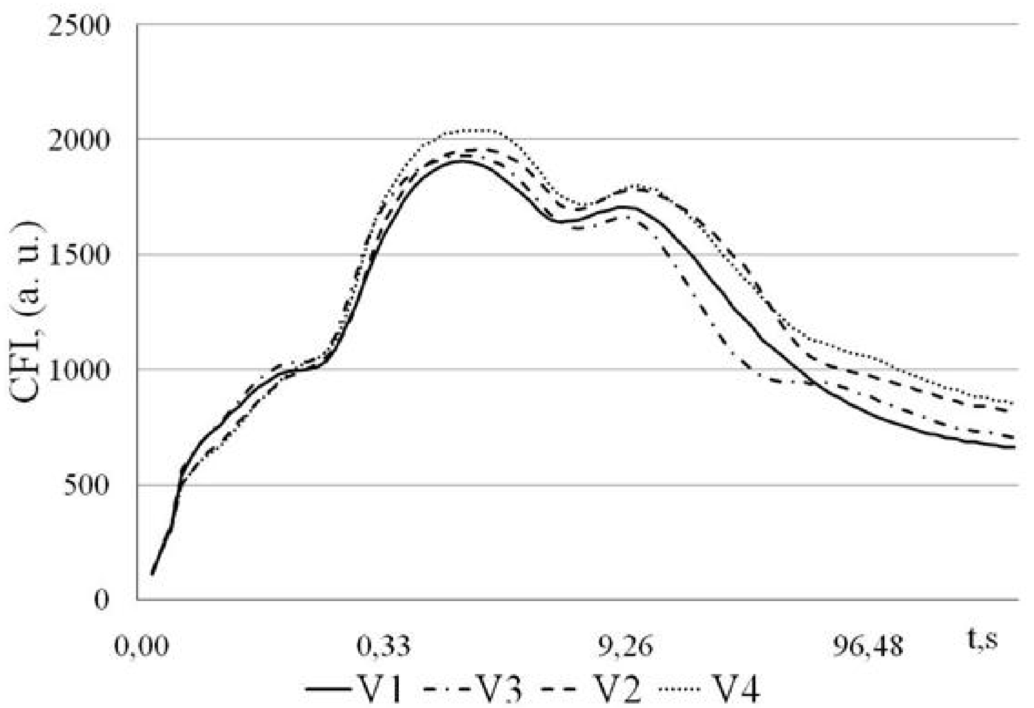

Figure 4. The intensity of chlorophyll fluorescence of goose-foot plant before of toxicant bringing in

The chlorophyll fluorescence intensity of test plants changed under the influence of toxicant. Figures 5 and 6 show graphs of the chlorophyll fluorescence on the second and third days of the impact of copper sulphate. It can be easily seen, that on the third day the maximum level of the chlorophyll fluorescence induction parameters (F_{st}, F_m) considerably decreased for plants that had been treated by toxicant.

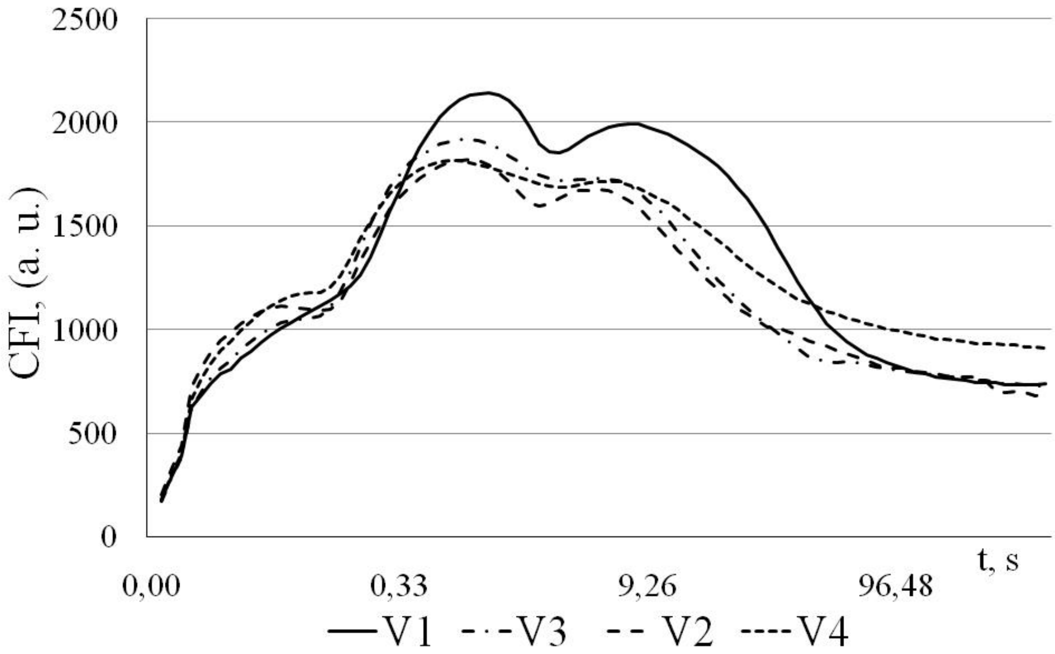

Figure 5. The intensity of chlorophyll fluorescence of goose-foot plant on the second day of toxicant influence

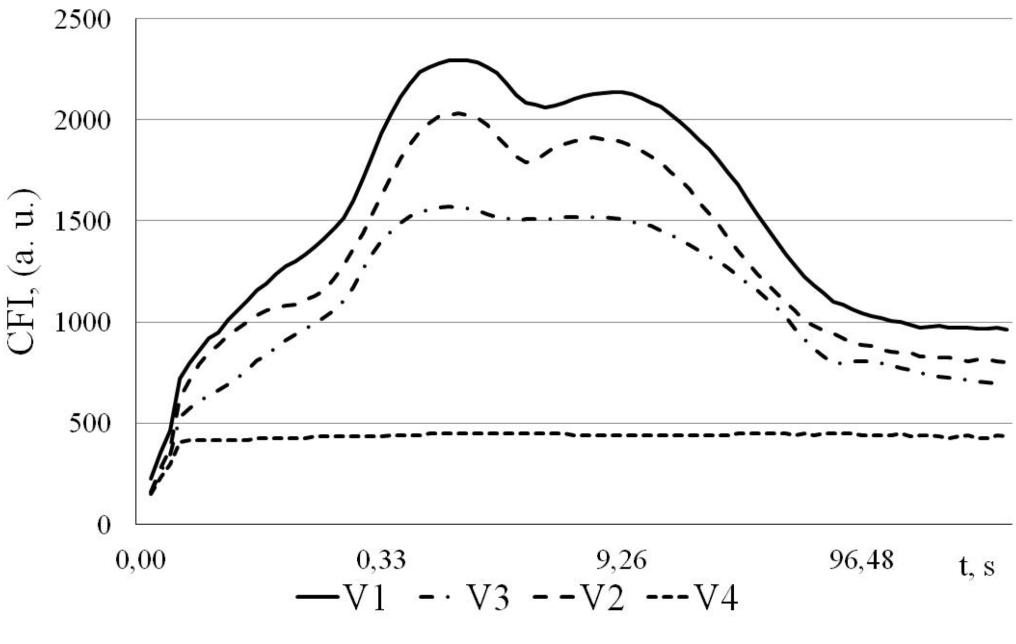

Figure 6. The intensity of chlorophyll fluorescence of goose-foot plant on the third day of toxicant influence

It should be noted, that on the sixth day of toxicant influence only one group of plants V2 remained, two other groups of plants V3 and V4 perished.

Analysis of parameter F_v/F_m provides information about the photochemical reactions, which are most sensitive to environmental factors. The maximum difference of the parameter F_v/F_m between the control group and the group V4, which received the maximum dose of copper sulphate, equals 38 %. At the beginning of the experiment this parameter had almost the same value in the three groups V1, V2, V3, V4 – 0,906 on the average. In the control group parameter F_v/F_m decreased by 5,8 % in comparison with the first day of measurement. In the group of plants V2 on the fifth day of toxicant influence the parameter F_v/F_m decreased by 5 % and the overall decrease equaled 4,6 % in comparison with the first day of experiment. The value of parameter in the group V3 decreased on the six day of the influence of copper sulphate. In the group V4 this parameter decreased by 39 % on the third day of the influence of toxicant. Figure 7 shows changes of the parameter during experiment.

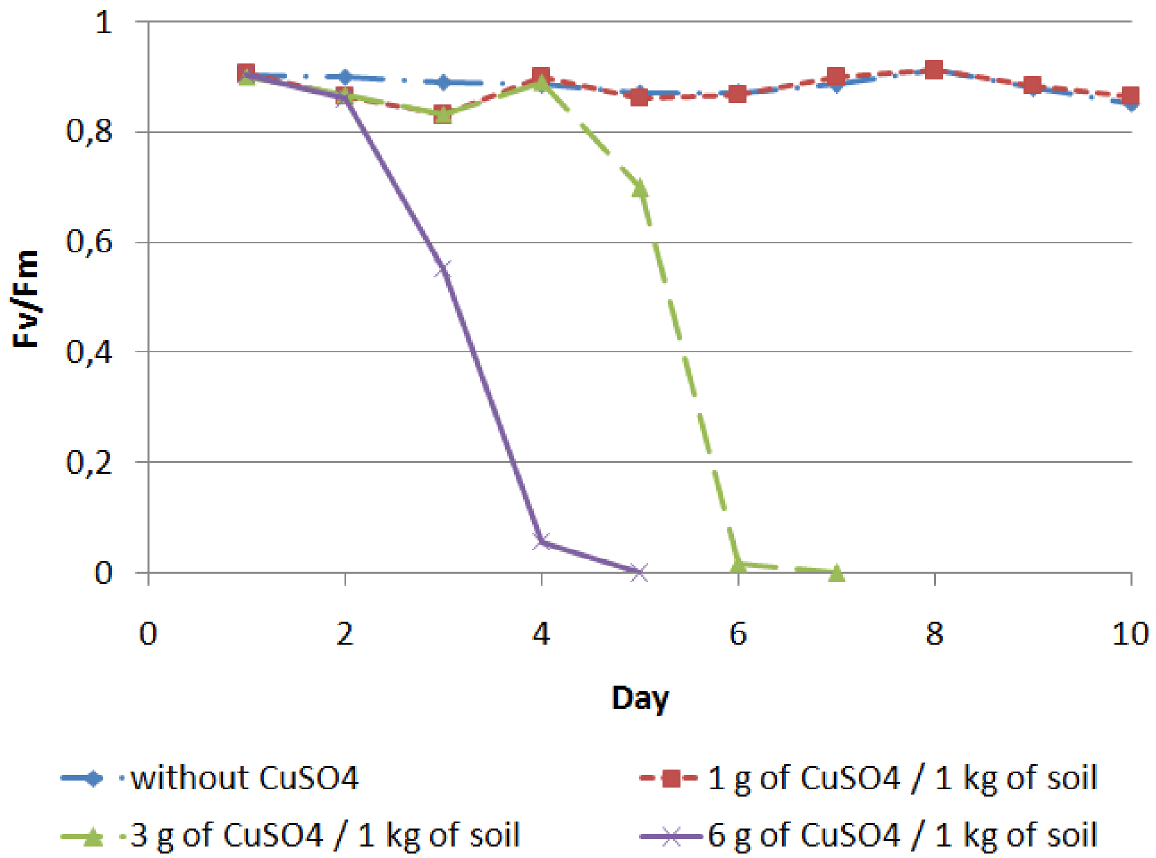

Figure 7. Changes of the parameter F_v/F_m during the testing

Analysis of results shows, that different doses of copper sulphate influenced on the photosynthetic apparatus of plants in different ways. Thus, the dose of 6 grams of copper sulphate was critical for plant of group V4. Also, the dose of 3 g of copper sulphate is critical for plants of group V3 and causes irreversible changes in the plants. Photosynthetic apparatus of plants, treated by 3 g of $CuSO_4$, stops to function on eighth day of toxicant influence. The dose of 6 grams breaks the photosynthetic processes in plants on the third day. However, it should be noted, that the dose of 1 gram of $CuSO_4$ does not cause any serious changes in plants and also does not break the photosynthesis of plants.

For developing methodical support for wireless biosensors the experiment was conducted to research the influence of heavy metals on plants. It allowed to estimate the dose of copper sulphate, that is critical for plants, and to determine informative parameters of chlorophyll fluorescence induction curves. During application of industrial methods the obtained results will be used to detect the presence of heavy metals in plants and estimate their impact on ecological state of certain territories.

Using neural networks for determination of plants under stress

Nowadays neural networks and widely used for the analysis of biological and agricultural data in viral diseases of plants, pest determination, water consumption estimation, plant quality estimation etc. [Samborska at al.].

Researches of influence of herbicide on chlorophyll fluorescence were conducted at the V.M. Glushkov Institute of Cybernetics and the enough amounts of data were gained for using neural networks. Herbicide Roundup (glyphosate) was used for experiments. Roundup is a broad-spectrum systemic herbicide. The plants of Datura stramonium (weed) were divided into three groups. One, control group was not treated and two others were sprayed with different doses of herbicide.

Two-layer feed-forward network was chosen for classification of curves. Neural network has 89 inputs and 3 outputs (every measured curve consist of 89 points). Second, output layer consist of three neurons (three variants of curves). The required number of neurons of hidden layer was determined by conducting series of experiments. The performance (P) of the training was evaluated using means square error.

There were trained neural networks with different number of hidden layer neurons (from 1 to 364). The training of every network was repeated 30 times and the results were averaged and combined in vector P_{mean} (figure 8). Thus, the neural network works most efficiently with not more than 70 neurons in the hidden layer. A neural network with 25 neurons in the hidden layer was chosen for further use. The network uses the sigmoid transfer function for hidden neurons and the softmax function for output neurons.

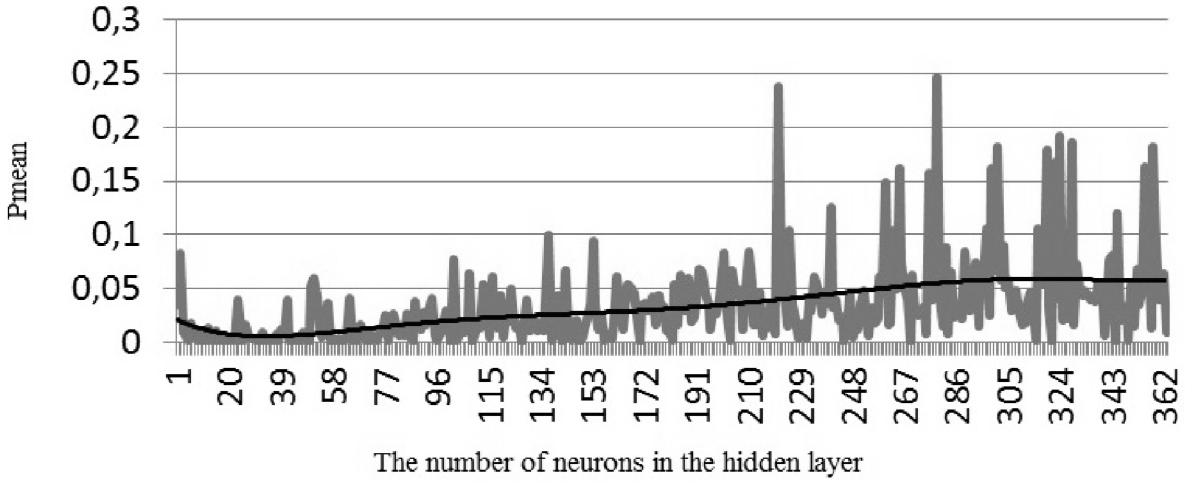

Figure 8. . Dependence of the mean square error of the neural network training on the number of neurons

The neural network was trained on data measured in different days. The data measured in different days were used separately for training of the network. The results of the training are presented in table 1.

As seen from table 1, the smallest errors of recognition were received with data in 7 and 11 days. It is known that Roundup breaks the synthesis of the amino acids on 5-6 day and plants wade and discolor after two weeks. But after two weeks the curves of chlorophyll fluorescence of the treated leaves had serious difference even on one plant, therefore the neural network recognition is unsatisfactory. On the contrary the Student's test confirmed the difference between curves of plants of different groups at the end of second week.

Thus we showed that neural networks can be trained for stress recognition of plants using curves measured by sensors developed at V.M. Glushkov Institute of Cybernetics of NAS of Ukraine.

It is useful to use neural network for creating methods for evaluation of the state of plants in the city and the farm. It can be used at the stage of making decision (start watering, give fertilizer, etc.). Neural network training needs a representative set of data to make valid managerial decision, so the wireless biosensor networks allow to receive enough number of fluorescence induction curves.

Table 1 Results of the neural network training using data measured in different days, where E is an error of training, Ev is an error of validation, Et is an error of testing, Em is a mean calculated from three previous errors.

The number of curves	E, %	Ev,%	Et,%	Em,%	Notes
40	64,3	66,7	33,3	60,0	Before treatment of the herbicide
43	16,1	33,3	66,7	25,6	Before treatment of the herbicide
41	0	33,3	50,0	12,2	The third day after treatment
43	80,6	66,7	83,3	79,1	The fifth day
43	0	0	33.3	4.7	The seventh day
30	0	0	20	3.2	The eleventh day
43	19,4	16,7	66,7	25,7	The thirteen day
21	3,2	0	66,7	11,6	The twentieth day

Using neural networks for determination of plants under stress

CFI curves of different plant species have some significant difference, thus they can be used for determination of specie of plant that are shown in [Kirova at al, 2009] by means of OJIP curve (CFI curve received during nearly 10 seconds) and neural network. With aim of testing the developed sensors for this task, a set of plants was measured. The set includes 176 curves from 6 species. The curves were measured during 5 minutes (full curve of CFI) and 10 seconds (OJIP curve) for next plants: soybean, goosefoot, ficus elastic, ficus benjamina, euphorbia, zinnia.

Two-layer feed-forward network with 89 inputs and 25 neurons in the hidden layer was chosen. The network uses the sigmoid transfer function for hidden neurons and the softmax function for output neurons as in previous experiment. The output layer consists of 6 neurons.

The results of testing of the neural network present in table 2. The neural network was trained 100 times and errors of testing were averaged after.

Table 2. The results of determination of plant species

Duration of measurement of CFI	5 minutes	10 seconds
minimal testing error, %	0	0
mean testing error,%	6,52	9,80

So, the curves of developed sensors can be used for taxonomic determination of plants. The curves measured during 5 minutes are more appropriate for this task. There are raised the issue of determination of plants with large amount of curves of very close species. The approach to solve it is described in [Kirova at al, 2009].

Conclusion

It was conducted the series of experiments for the testing biosensors developed at the V.M Glushkov Institute of Cybernetics of NAS of Ukraine to determine the sensitivity of biosensors to influence of stressful factors of different nature on experimental plants. The suitable software and database were developed to facilitate data processing. As result of using neural network, it can be concluded that neural network can recognize the different dose of fertilizer before changing of leaves appears and a 5 minutes measurement of CFI is more informative for determination of plant species then 10 seconds measurement.

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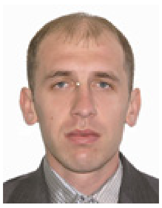

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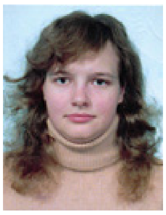

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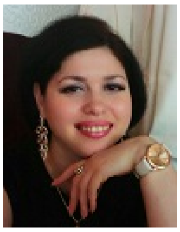

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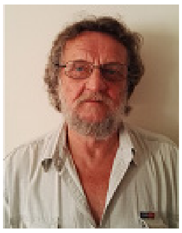

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AUTOMATON MODEL OF ONE STATISTICAL RULE

Tariel Khvedelidze

Abstract: *In the paper, a construction (algorithm of behavior) of a finite automaton in a stationary random environment with three possible reactions (win, loss, indifference) is proposed. It is constructed on the basis of a known statistical rule from the theory of recurrent events: "either a series of successes of length m, or a series of failures of length l". With methods of the theory of random walks, a formula is obtained for the generating function of the probability of changing the action of the finite automaton under consideration. It is shown that the sequence of finite automata of the construction under consideration converges to the corresponding infinite (with countably many states) automaton of the same structure and its possible behavior is investigated.*

Keywords: *finite automaton, stationary random environment, behavior algorithm, generating function, expediency of behavior.*

ITHEA keywords*: G.3 Probability and Statistics*

Introduction

The problem of the behavior of a finite automaton in a binary stationary random environment was formulated and developed by M. L. Tsetlin [1]. The environment in the simplest case reacts to the actions of the automaton in two ways: either "punishes" or "encourages" the automaton with certain probabilities. The automaton a priori information about the medium does not have an. Then different authors the proposed various constructions of asymptotically optimal sequences of automata in both binary and non-binary stationary random environment (see, for example, [2-7]). For automata belonging to such a sequence, the mathematical expectation of the win increases with an increase in the memory capacity of the automaton and tends to the maximum possible in a given stationary random environment.

In the interest of technical applications, the synthesis problems of automata optimal at various criteria in a binary and ternary stationary random environment were investigated in [8-9].

However, studies related to the study of the behavior of automata in both binary and non-binary stationary random environments have shown that the construction of an automaton that is best for some feature in any medium is unrealistic. Therefore, it is necessary to construct structures and develop analytical and numerical methods for finding statistical characteristics of the behavior of wide classes of automata that can be used to solve various practical problems.

In the present paper, on the basis of a known statistical rule from the theory of recurrent events: "either a series of successes of length m, or a series of failures of length l" we propose a construction (algorithm of behavior) of the finite automaton in a stationary random environment with three possible reactions (win, loss, indifference). With methods of the theory of random walks, received a formula is obtained for the generating function of the probability of changing the action of the finite automaton under consideration. It is shown that the sequence of finite automata of the construction under consideration converges to the corresponding infinite (with countably many states) automaton of the same structure and its possible behavior is investigated.

The functioning of the finite automaton $T_{2n,2}(l,m)$ in a ternary stationary random environment

Consider the known scheme of behavior of automata in a random environment [1] and assume that all possible reactions $S\epsilon\{s_1, s_2, \dots, s_g\}$ of the environment C are perceived by the automaton, unlike [1], as belonging to one of the three classes - class favorable reactions (win, s = + 1), to the class of adverse reactions (loss, s = -1) and to the class of neutral reactions (indifference, s = 0).

Definition. Will say that the automaton A_k functions in a ternary stationary random environment $C(a_1, r_1; a_2, r_2; \dots; a_k, r_k)$, if the actions of the automaton and the values of the input signal are connected as follows: if the automaton performs the action $f_\alpha(\alpha = \overline{1;k})$, then the medium $C(a_1, r_1; a_2, r_2; \dots; a_k, r_k)$ forms the signal value $s = +1$ at the input of the automaton with the probability $q_\alpha = \frac{1-r_\alpha+a_\alpha}{2}$, the value of the signal $s = -1$ with the probability $p_\alpha = \frac{1-r_\alpha-a_\alpha}{2}$ and the value of the signal $s = 0$ with the probability $r_\alpha = 1 - q_\alpha - p_\alpha$ $(\alpha = \overline{1;k})$.

Here the quantity $a_\alpha = q_\alpha - p_\alpha$ ($|a_\alpha| < 1\text{-}r_\alpha$) has the meaning of the mathematical expectation of the payoff for the action f_α in the environment $C(a_1, r_1; a_2, r_2; \dots; a_k, r_k)$. In solving problems of analyzing the possible behavior of an automaton in some random environment, by changing the numbering of the actions of the automaton, one can achieve that $a_1 > a_2 \geq \dots \geq a_k$, i.e. in the environment $C(a_1, r_1; a_2, r_2; \dots; a_k, r_k)$ the action f_1 of the automaton A_k with the average win a_1 is optimal.

Let the finite automaton $T_{2n,2}(l,m)$, which has $2n$ $(n = l + m - 1)$ internal states $L^{(n)} = L_1^{(n)} \cup L_2^{(n)} = \{-(l + m - 1), \dots, -2, -1, 1, 2, \dots, (l + m - 1)\}$ and can perform two different actions f_1 and f_2, functions in a ternary stationary random environment $C(a_1, r_1; a_2, r_2)$.

We define the tactics of the behavior of the automaton $T_{2n,2}(l,m)$ in the environment $C(a_1,r_1;a_2,r_2)$ as follows: if the signal value $s=+1$ (win) arrives at the input of the automaton, then the automaton from any state x of the area $L_\alpha^{(n)}$ goes to the state $|x|=l$ of the same area; at a signal $s=-1$ (loss), the automaton passes from the state $|x|=i$, $(i=l,l+1,\dots,l+m-1)$ to the state $|x|=l-1$, and from state $|x|=i$, $(i=2,3,\dots,l-1)$ - in the state $|x|=i-1$; the state $x=1$ goes in the state $x=-l$, and the state $x=-1$ - to the state $x=l$. At the signal $s=0$ (indifference), the automaton passes from the state $|x|=i$ $(i=1,2,\dots,l)$ to the state $|x|=l+1$, and from the state $|x|=i$ $(i=l+1,\dots,l+m-2)$ - in the state $|x|=i+1$; the state $x=l+m-1$ goes to the state $x=-l$, and the state $x=-(l+m\text{-}1)$ - to the state $x=l$ (Fig.1).

Thus, the automaton $T_{2n,2}(l,m)$ has one input and two outputs: the input state in the area L_α, $\alpha=1,2$ is the state with the number $|x|=l$, and the output states are states with numbers $|x|=1$ and $|x|=l+m-1$.

It is easy to see that the automaton $T_{2n,2}(l,m)$ changes the action if its input receives a penalty of length l or indifference of length m and it is an automaton analogue in the ternary stationary random environment of the known statistical rule from the theories of recurrent events: "Either a success series of length l, or a series of failures of length m " [10]. We note that an automaton realization of this rule in a binary stationary random environment was considered in [11].

To study the possible behavior of an automaton in a stationary random environment $C(a_1,r_1;a_2,r_2;\dots;a_k,r_k)$, are initial the following statistical characteristics of the behavior [4]: the probabilities σ_α change (ever) the action f_α and the mathematical expectations of a random time τ_α before the change of action f_α by at starting from the state $x\in L_\alpha$, $\alpha=\overline{1;k}$.

We denote by $u_{x,d}^{(n)}$ the probability that the automaton $T_{2n,2}(l,m)$ at the instant d changes for the first time the action f_α, starting from any state with the number x of the domain L_α.

Taking into account the behavior of the automaton $T_{2n,2}(l,m)$ in the stationary random environment $C(a_1,r_1;a_2,r_2)$, with respect to the probabilities $u_{x,d}^{(n)}$, we obtain the following difference equation

$$u_{x,d}^{(n)}=pu_{x-1,d}^{(n)}+ru_{l+1,d}^{(n)}+qu_{l,d}^{(n)},\quad x=1,2,\dots l, \tag{1}$$

$$u_{x,d}^{(n)}=pu_{l-1,d}^{(n)}+ru_{x+1,d}^{(n)}+qu_{l,d}^{(n)},\qquad x=l+1,\dots,l+m-1, \tag{2}$$

$$d=0,1,2,\ \ .\ .\ .$$

and the boundary conditions arising from the probabilistic meaning of $u_{x,d}^{(n)}$

$$u_{0,0}^{(n)}=1,\ u_{l+m,0}^{(n)}=1,\ u_{x,0}^{(n)}=0\quad \forall x\neq 0,l+m. \tag{3}$$

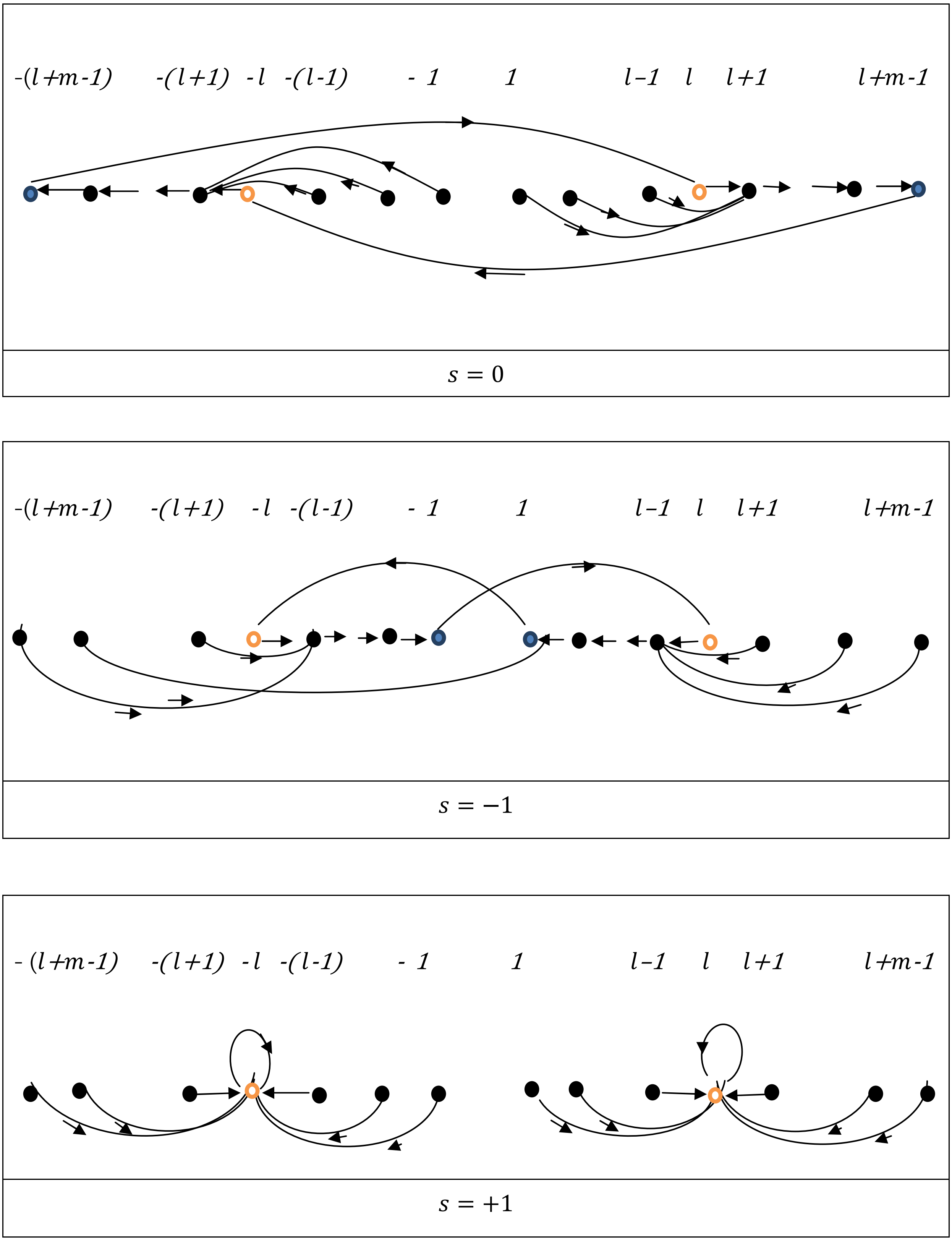

Fig.1. The graph of transitions between the states of the automaton $T_{2n,2}(l,m)$ in the area $L_\alpha, \alpha = 1{,}2$ at the signal $s = 0, \ s = -1, \ s = +1$.

Relative to the generating function of the probability of a action change

$$U_x^{(n)}(z) = \sum_{d=0}^{\infty} u_{x,d}^{(n)} z^d,$$

from (1) - (3) we obtain the boundary value problem

$$U_x^{(n)}(z) = pzU_{x-1}^{(n)}(z) + rzU_{l+1}(z) + qzU_l^{(n)}(z), \quad x = 1,2, \dots, l, \tag{4}$$

$$U_{l+x}^{(n)}(z) = rzU_{l+x+1}(z) + pzU_{l-1}^{(n)}(z) + qzU_l^{(n)}(z), \quad x = 1, \dots, m-1, \tag{5}$$

$$U_0^{(n)}(z) = 1\,, \ U_{l+m}^{(n)}(z) = 1. \tag{6}$$

From (4) - (6) we finally obtain that for the generating function $U_x^{(n)}(z)$ the action changes of the automaton $T_{2n,2}(l,m)$

$$U_l^{(n)}(z) = \frac{(1-pz)(pz)^l[1-(rz)^m] + (1-rz)(rz)^m[1-(pz)^l]}{1 - z + (pz+qz)(rz)^m + (qz+rz)(pz)^l - (1+qz)(rz)^m(pz)^l}.$$

The functioning of the finite automaton $T_{2n,2}(l,m)$ in the environment $C(a_1, r_1; a_2, r_2)$ is described by a finite homogeneous ergodic Markov chain. For finite automata the probabilities $\sigma_\alpha^{(n)}$ of the change of the action f_α are equal to one, and the mean times $\tau_\alpha^{(n)}$ are finite in any non-degenerate ($|\, a_\alpha \,| \neq 1 - r_\alpha$) environment $C(a_1, r_1; a_2, r_2)$. Consequently, according to [4], the optimality of the behavior of a finite automaton is excluded and the quality of its behavior is determined by the degree of expediency of its functioning.

By the definition of [1-4], the automaton A_k has a expediency behavior in a stationary random environment $C(a_1, r_1; a_2, r_2; \dots; a_k, r_k)$, if

$$M(A;C) > M_0, \tag{7}$$

where $M(A_k;C)$ is calculated by the formula

$$M(A_k;C) = \frac{\sum_{i=1}^{k} a_i \tau_i^{(n)}}{\sum_{i=1}^{k} \tau_i^{(n)}}, \tag{8}$$

and

$$M_0 = \frac{1}{k}\sum_{i=1}^{k} a_i$$

is the mathematical expectation of winning if the automaton with equal probability chooses its actions regardless of the reaction of the environment. Note that if $M(A_k;C) = M_0$, then the automaton is indifferent, and if $M(A_k;C) < M_0$ - is inexpedient.

Taking into account (7) and (8), for the expediency behavior of the automaton $T_{2n,2}(l,m)$ in the environment $C(a_1, r_1; a_2, r_2)$ the following condition must be fulfilled: $\tau_1^{(n)} > \tau_2^{(n)}$.

Accordingly, at $\tau_1^{(n)} = \tau_2^{(n)}$ the behavior of the automaton is indifferent, at $\tau_1^{(n)} < \tau_2^{(n)}$ - the behavior of the automaton is inexpedient.

For the automaton $T_{2n,2}(l,m)$ the statistical characteristics of the behavior - $\sigma_{l,\alpha}^{(n)}$ and $\tau_{l,\alpha}^{(n)}$ are calculated using the generating function:

$$\sigma_{l,\alpha}^{(n)} = U_l^{(n)}(z)\,|_{z=1} = 1,$$

$$\tau_{l,\alpha}^{(n)} = \frac{dU_l^{(n)}(z)}{dz}\,\Big|_{z=1} = \frac{(1-p_\alpha^l)(1-r_\alpha^m)}{(1-p_\alpha)p_\alpha^l+(1-r_\alpha)r_\alpha^m-(1+q_\alpha)p_\alpha^l r_\alpha^m} < \infty\,,\ \alpha = 1,2.$$

In the particular case, at $l = m = 1$, the behavior of the automaton $T_{2n,2}(1,1)$ in the environment $C(a_1, r_1; a_2, r_2)$:

- expedient, if $q_1 > q_2$;
- indifferent, if $q_1 = q_2$;
- inadvisable, if $q_1 < q_2$.

The functioning of the infinite automaton $T_2(l,m)$ in a ternary stationary random environment

Consider we now the functioning of the infinite (with a countable number of states) analog $T_2(l,m)$ of the automaton $T_{2n,2}(l,m)$ in the stationary random environment $C(a_1, r_1; a_2, r_2)$, the subsets of the states L_α $(\alpha = 1,2)$ of which are equally powerful.

Let $u_{x,d}$ be the probability that the automaton $T_2(l,m)$ at the instant of time d first changes the action of f_α, starting from any state with the number x of the area L_α.

Assume that l is fixed and $m \to \infty$ $(n = l + m - 1 \to \infty)$.

Then, taking into account the probabilistic meaning of the quantity $u_{x,d}$ and the construction of the infinite automaton $T_2(l,\infty)$, with respect to the generating function of the probability of changing the action

$$U_x(z) = \sum_{d=0}^{\infty} u_{x,d}\, z^d$$

we have the boundary value problem

$$U_x^{(n)}(z) = pzU_{x-1}^{(n)}(z) + (rz + qz)U_l^{(n)}(z), \quad x = 1,2,\ldots,l, \qquad U_0^{(n)}(z) = 1. \tag{9}$$

The solution to this problem is:

$$U_l(z) = \frac{(1-pz)(pz)^l}{1 - z + (qz + rz)(pz)^l}. \tag{10}$$

With the help of (10), the probability characteristics $\sigma_{l,\alpha}$ and τ_α are computed:

$$\sigma_{l,\alpha} = U_l(1) = 1, \qquad \tau_{l,\alpha} = \frac{dU_l(z)}{dz}\Big|_{z=1} = \frac{(1-p_\alpha^l)}{(1-p_\alpha)p_\alpha^l} < \infty,\ \alpha = 1,2.$$

Now let m be fixed and $l \to \infty$ $(n = l + m - 1 \to \infty)$. Then, renumbering the states of the automaton in the reverse order, it is easy to verify that the generating function of the probability of changing the action is a solution of the boundary value problem (9), if in it we replace l by m, p by r and r by p.

The solution obtained has the following form

$$U_m(z) = \frac{(1-rz)(rz)^m}{1 - z + (qz + pz)(rz)^m}$$

and

$$\sigma_{l,\alpha} = U_m(1) = 1, \qquad \tau_{l,\alpha} = \frac{dU_m(z)}{dz}\Big|_{z=1} = \frac{(1-r_\alpha^m)}{(1-r_\alpha)r_\alpha^m} < \infty,\ \alpha = 1,2.$$

If $l \to \infty$ and $m \to \infty$, then the infinite automaton forever remain in the subset of states in which it was at the initial instant of time. In this case $U_l(z) = 0$ and $\sigma_{l,\alpha} = 0$, $\tau_{l,\alpha} = \infty$.

Thus

$$\lim_{m\to\infty} U_l^{(n)}(z) = U_l(z), \qquad \lim_{l\to\infty} U_l^{(n)}(z) = U_m(z), \qquad \lim_{\substack{l\to\infty \\ m\to\infty}} U_l^{(n)}(z) = U_l(z) = 0.$$

Thus, the sequence of finite automata $\{T_{2n,2}(l,m)\}_{l=1}^{\infty}$, $\{T_{2n,2}(l,m)\}_{m=1}^{\infty}$ and $\{T_{2n,2}(l,m)\}_{l,m=1}^{\infty}$ converges to the corresponding infinite automata $T_2(\infty,m)$, $T_2(l,\infty)$ and $T_2(\infty,\infty)$ for the same structure and, consequently, the asymptotic behavior of the finite automaton $T_{2n,2}(l,m)$ under consideration is defined, as in [4], by the behavior of the corresponding infinite automaton $T_2(l,m)$.

Conclusion

Analysis of the results obtained, taking into account the condition $a_1 > a_2$, makes it possible to draw the following conclusion.

1. The behavior of the infinite automaton $T_2(\infty,\infty)$ in the environment $C(a_1,r_1;a_2,r_2)$ is indifferent.
2. The behavior of the infinite automaton $T_2(\infty,m)$ in the environment $C(a_1,r_1;a_2,r_2)$ is:
   - expedient, if $r_1 < r_2$;
   - inexpedient, if $r_1 > r_2$;
   - indifferent, if $r_1 = r_2$;
3. The behavior of the infinite automaton $T_2(l,\infty)$ in the environment $C(a_1,r_1;a_2,r_2)$ is:
   - expedient, if $p_1 < p_2$;
   - inexpedient, if $p_1 > p_2$;
   - indifferent, if $p_1 = p_2$.

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Scientific Research: Modeling and Control of Complex Systems

VISION-BASED APPROACH TO UAV VIBRATION ANALYSIS[1,2]

David Asatryan, Samvel Hovsepyan

***Abstract**: It is known that the vibration of the board of unmanned aerial vehicles (UAVs) leads to distortions of information received from UAV. An important task is to determine the vibration parameters of the UAV board in real flight conditions at the absence of special measuring equipment on the board. The source of the necessary information for this can serve as a video sequence taken by the on-board video camera, since vibration leads to blurring of the image. In this paper, a technique for estimation of vibration parameters by a method of the analysis of the degree of blurring of the images in the frames of a video sequence is proposed. In this paper, we use the method proposed earlier, based on the determination of the Weibull distribution shape parameter, calculated from the set of gradient magnitudes of the image. The frequency of vibration is determined by analyzing the spectral density of the sequence of estimates of the blur. An example of real measurements carried out with the help of UAV is given.*

Keywords: UAV, Vibration, video, Weibull distribution, spectral density.

***ACM Classification Keywords**: Image Processing and Computer Vision*

Introduction

Unmanned aerial vehicles (UAVs) have become an active research topic in photogrammetry in problems of determining the position, orientation and geometric dimensions of certain ground objects, etc. [1].The successfulness of this task is due to the possibility of obtaining high-quality digital photos and applying effective image processing algorithms. Modern UAVs are equipped with high resolution cameras, in principle, sufficient for solving many photogrammetric problems.

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However, images obtained from on-board equipment are distorted due to a number of factors inevitably accompanying the flight of any UAVs such as the influence of weather conditions (in particular, winds), random deviations from the intended flight path, turbulence of the atmosphere, vibration of the board from running engines, etc. As a result, the image is blurred, noised and distorted in an unexpected manner, which significantly affects the accuracy of the photogrammetric measurements. According to [2] a one-pixel shift in a 0.8 mega pixel resolution captured from a UAV operating at 1000ft will correspond to about 2.5m measurement error on the ground. Therefore, studies related to the assessment and reduction of the effect of vibration on the quality of decisions taken on the information delivered by UAVs has found great attention in the scientific literature.

One of the important tasks in this area is to assess the impact of vibration of the UAV position in space and, consequently, the position of the video camera on the degree of blurring of images in the video sequence. In general, vibration can be regarded as a special type of motion, which has the form of periodic oscillations. Consequently, the above estimation problem can be reduced to determining the parameters of these oscillations.

The task of evaluating the vibration parameters of a UAV by photographing certain objects is considered in different formulations. The most common approach is to develop and perform experiments using shaker stands. For example, in [3] the problem of Automatic isolation of blurred images from UAV image sequences is considered. A "shaking table" was used to create images with known blur during a series of laboratory tests. Once defined for a sequence of images, a user defined threshold can be used to differentiate between "blurred" and "acceptable" images.

As for image processing based methods, video stabilization is attained through image processing techniques to estimate the camera motion by computing the degree of geometric transform parameters between consecutive frames of video, smooth the parameters and compensate the deviation of images [4].

Another approach is used in [5], in which to study the characteristics of the vibration of the UAV side, the most significant sources of vibration are selected and the effects of individual components and total vibration are simulated. However, this approach involves performing work to assess the degree of vibration influence only for a certain type of UAV and the possibility of distributing the results obtained to other types of products remains unclear.

We are interested only in those methods that allow us to solve the above-mentioned problem with a real UAV flight or in conditions as close as possible to real flight. It is clear that the use of expensive measuring stands and other special equipment on board the UAV is impractical, even if it is possible. Therefore, we are interested in methods that use video equipment, with which certain objects are photographed and on the images obtained the corresponding decisions are taken.

The main idea of the proposed approach is based on the fact that the images in frames of the video sequence obtained during real UAV flight are subject to blurring, the degree of which fluctuates from frame to frame and can fluctuate according to the camera position at each moment of time. This circumstance makes it possible to estimate the frequency of the vibration of the bead, and also to carry out relative measurements of its amplitude. The proposed approach is applied for the first time and can be applied in other related fields.

Technique for estimating the frequency of vibration

A method for estimating the frequency of vibration is based on the use of the image blur measure proposed in [6] to analyze the frames of the video sequence obtained from the UAV. This measure represents the value of the form parameters of the two-parameter Weibull distribution (1),

$$f(x;\eta,\sigma)=\frac{\eta}{\sigma}\left(\frac{x}{\sigma}\right)^{\eta-1}\exp\left[-\left(\frac{x}{\sigma}\right)^{\eta}\right],\ x\geq 0, \quad (1)$$

adjusted to the set of gradient magnitudes of the image, calculated using the Sobel operator [7], where $\eta>0$ is the shape parameter, and $\sigma>0$ is the scale parameter. We note that the Weibull model of the gradient magnitude is useful for other problems of image processing (see, for example, [8-11]).

In [2], a sufficiently sharp monotonically increasing dependence of this measure on the degree of blurring of the image is shown, approaching the value of "2", and in some cases slightly exceeding this value.

We give an example illustrating what was said for a particular image. In Fig. 1 is shown an example of an image blurred with a fixed smoothing algorithm with different values of the blur factor. The values of the shape parameter η are shown below the corresponding images. It can be seen that the dependence of the evaluation of the form parameter on the degree of blurring is consistent with what was said above and visual perception.

Numerous experiments with the processing of video sequences obtained in real UAV flight have shown that fluctuations of the blur measure are actually observed. Let us give an example. In Fig. 2, a fragment of the fluctuation dependence of the blur measure from number of the video sequence frames obtained with the real drone of the Ar Drone 2.0. Here the shooting frequency is 30 frames per second. Numerous experiments with the processing of video sequences obtained in real UAV flight have shown that the fluctuations of the blur measure are actually observed.

0.799 0.890 1.082 1.472 1.631

Fig. 1. Estimates of the shape parameter η for the blurred Lena image

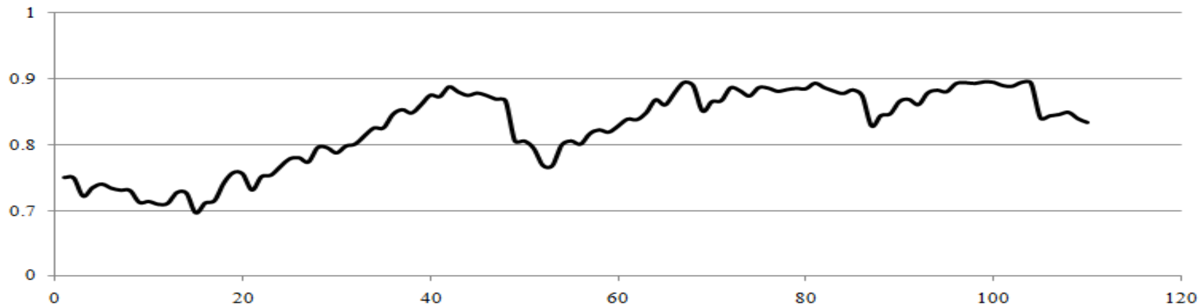


Fig.2. Fragment of the curve of the blur measure changing in real video frames.

High-frequency oscillations observed on the curve correspond to changes in blur due to vibration, while low-frequency variations represent a change in the degree of blurriness of the observed frames during the movement of UAVs on the terrain.

To estimate the vibration frequency, a spectral analysis of this curve was carried out. In Fig. 3 is shown the spectral density curve calculated along this curve by means of Fast Fourier Transform algorithms (processing is performed using the STATISTICA10 package). The curve shows two spectral density peaks corresponding to frequencies of about 5 Hz and 15 Hz.

In order to verify the correctness of the experiment, spectral density calculations were made for 10 consecutive segments of the video sequence containing 30 frames (i.e., with a duration of 1 second).

Two fragments of this experiment are shown in Fig. 4. It turned out that the estimation of the vibration frequency is approximately the same for all segments, which confirms the correctness of the experiment and allows the evaluation to be carried out for the entire video sequence.

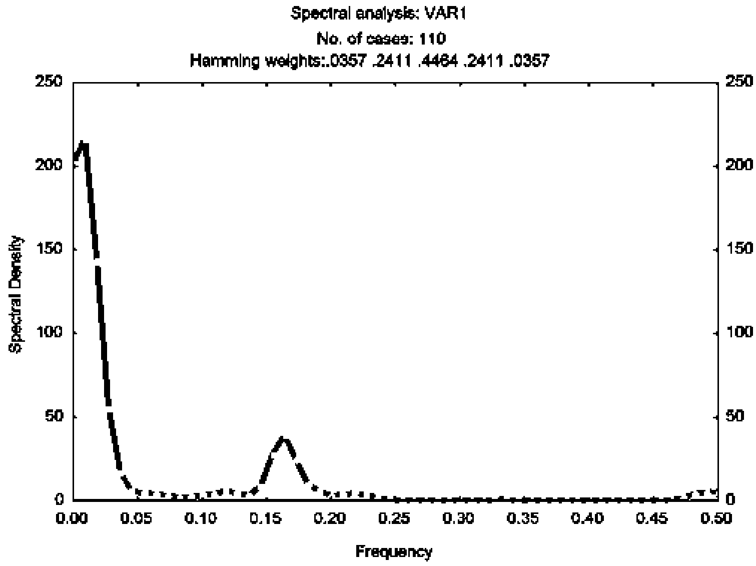
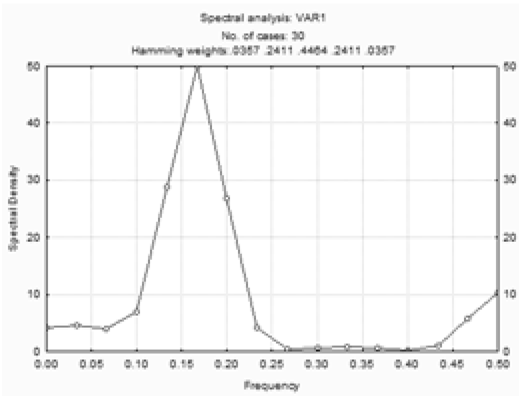
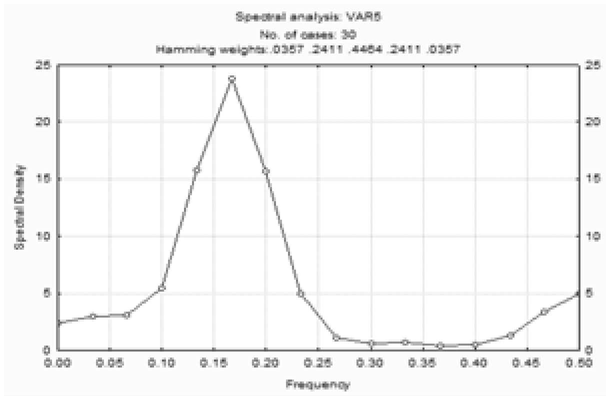


Fig.3. The spectral density calculated for the data of Fig. 2.





a) b)

Fig. 4. Spectral density for different segments of the video sequence.

a) For frames with numbers 1-30; b) For frames with numbers 91-120.

In conclusion, we describe one side, but important application of the proposed methodology. When photogrammetric measurements performed on video images obtained from the UAV board, it becomes necessary to select the most suitable frame for further processing. The purpose of this choice is to improve the accuracy of photogrammetric measurements. One of the criteria for selecting the desired frame is the degree of motion blur caused by the movement of the UAV. A similar problem was posed in [9], and, as pointed in the introduction of this paper, it is solved using measurements on a shake table. The same methodology allows to solve this problem in those cases when there is no such data and the only source of information is the video sequence obtained from the UAV. Then the application of the considered technique for the choice of the required frame is proposed based on the magnitude of the image blurriness in the frame.

Conclusion

In this paper, a technique is proposed for estimating the vibration frequency of the UAV side by properly processing the images of the video sequence. A technique for determining the blurriness of images in frames by the value of the Weibull distribution shape parameter, estimated from the set of the gradient magnitudes, was realized. The advantage of the proposed approach is the possibility of estimating the vibration parameters based on the results of video shooting in real flight conditions. The developed technique can be used in various photogrammetric problems, as well as in problems of monitoring conditions and flight processes of UAV.

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ERRATUM

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In the paper: David Asatryan, Karen Egiazarian, Vardan Kurkchiyan. Orientation Estimation with Applications to Image Analysis and Registration (International Journal "Information Theories and Applications", Vol. 17, Number 4, pp. 303-311, 2010) was made an error.

Formula (5) must be as follows

$$tg\alpha = \frac{2*\sigma_H \sigma_V \rho_{HV}}{\sigma_H^2 - \sigma_V^2 - \sqrt{(\sigma_H^2 - \sigma_V^2)^2 + 4\sigma_H^2 \sigma_V^2 \rho_{HV}^2}}.$$

Reminder is right.

TABLE OF CONTENTS OF IJ ITA VOL. 24, NO.:1, 2017

TABLE OF CONTENTS OF IJ ITA VOL. 24, NO.:2, 2017

TABLE OF CONTENTS OF IJ ITA VOL. 24, NO.:3, 2017

TABLE OF CONTENTS OF IJ ITA VOL.24, NO.:4, 2017