THE IMPACT OF THE MSDF TECHNOLOGIES ON THE INFORMATION SPACE STRUCTURE REORDERING AND EVOLUTION[1]

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The foundations of MultiSensor Data Fusion (MSDF) are universally related to the Information Space paradigm. As one of the most promising 21st century strategic areas of study, MSDF is a driving mechanism of the System of Systems, Information Dominance and Cyber-war concepts which emerge as main instruments of Information Warfare.[2] Technologies created in the framework of this concept are the technologies of the 21st century, and the question which science community is faced with is: *What is the relation between the rapidly developing MSDF instruments and the widespread futuristic concepts of Information Society, Information Security and Information Warfare*? Obviously the question is at the base epistemological level and the answer is not trivial.

Information Space and MSDF Technology

There are different views on MSDF. The main group of specialists is engaged in building specialized intelligent technologies, systems and tools as products, born by everyday problem solving needs. However, they are aware of the emerging acute need for a new general concept of MSDF. Stimulated by explosive development of sensors and sensor technologies,[3] the real challenge for the 21st century is to create *autonomous automatic MSDF systems* endowed with Artificial Intellect and to realize one of the best ideas of the science community to build *Artificial Intellect with autonomous self-learning functions*. The problem of utmost importance today is whether a feasible paradigm for such development exists.

From our point of view, the new MSDF technology will originate from consensus on the way fundamental definitions are perceived. There are striking differences between interpretations given for such well known notions as *signal, data, knowledge, culture, information*, etc. Dissension originates from the absence of effective consolidating metaphor. In order to create a unified MSDF understanding, it is necessary to start

with the development of an axiomatic and computer-oriented base, i.e., to formulate a unified concept and new vision for the information realm named *Information Space*.

Of prime importance is to understand the general tendencies in MSDF theory and practice. To achieve this, we have to integrate and to interpret into more universal information space paradigm the meanings of emerging terms such as information dominance, system of systems, information deterrence, OODA cognitive loop, etc. Thus, the nature of MSDF, as a separate area of R&D, will be understood in the framework of a common model, independent of the particular system application area. Which is the foundation of such a model? Is there a way to create it from existing R&D achievements?

A variety of particular understandings related to different general views on information processing, sensor systems theory,[4] data fusion automation,[5] estimation theory,[6] artificial intelligence,[7] etc., serve as donors for the current MSDF knowledge set composed of various mathematical methods and techniques.[8] This set reproduces contemporary views and highlights different operational aspects of MSDF.

Computer specialists in MSDF place special emphasis on hardware and software architecture design and adjustment to the environmental situation, on factors yielding complicated computational uncertainty problems, or complex engineering situations.

Radar and navigation specialists focus on filtering, detection and state estimation techniques, and on models of volatile situations and complex threats identification. The search for radar and navigation specifics of MSDF phenomena through sensors outputs networking, parallel detection and filtering, chaotic/stochastic models identification and feature measurement utilization, constitute the main directions of the contemporary theory of digital signal and data processing.

Artificial intelligence highlights the ability to cope with the changing nature and features of situations and threats.[9] The search for new mechanisms of MSDF through fuzzy logic, neural networks, and complexity theory defines the main stream of new soft-computing[10] applications.

The specific integrated view which encompasses all these different considerations may be found using the conceptual description of the Information Space metaphor, proposed in 1986 by M.V. Arapov as a 3D representation of the Global Information Infrastructure.[11] The construction of information circulation, carriers and processing flows (in terms of formal information media) was proposed as a general paradigm of the universal model of Information Space (I_S):

$$I_S = < C_R, C_T, C_C, S, O >,$$

where C_R is the information objects circulation *range* (or *Information Space Strata*

Range), C_T - information objects circulation *time* (or *Information Space Memory*), C_C - information objects circulation *quantity* (or *Information Space Multiplicity*), S - information space subjects, and O - information space *objects*.

Three types of *Information Strata Object's Units* were used by Arapov to interpret the *objects of information processing* as shown in the table below:

Stratum	Information Objects Units
Signal/Data	Pulse (Electro-Magnetic, Electric, Optical, Infrared, Physical, Nuclear, Biological)
Knowledge	Measurement, Image, Message, Model, Idea, Solution, Decision, Situation, Threat
Culture	Work of Arts, Musical Composition, Literature, Vision, Organization, Philosophy

As a result, a 3D model was constructed, where information exists in three different qualitative states: *signals/data, expert knowledge and culture* (Fig.1).

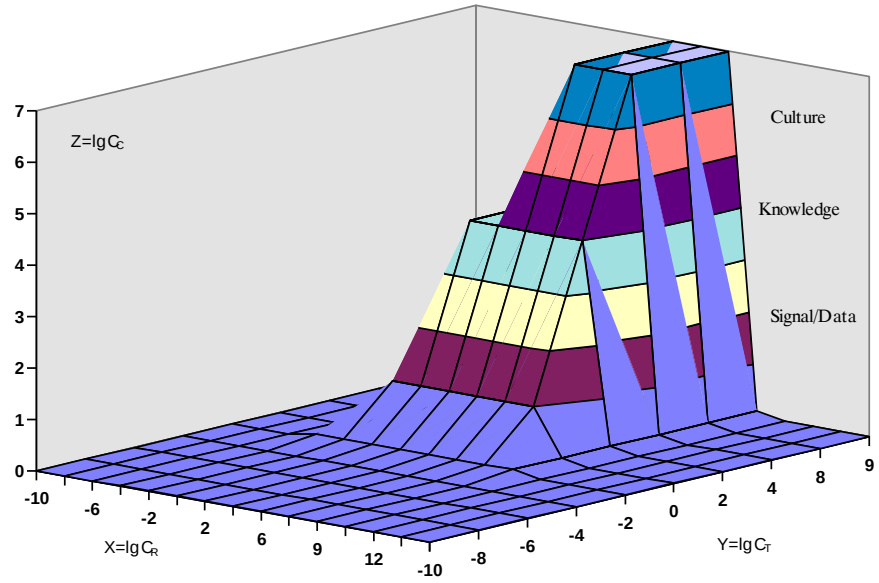

Figure 1: Arapov's Information Space Model (1986)

All levels of information processing are depicted at a higher level of abstraction and inference. The resulting structure can be used as general interpretation of Information Space, which incorporates the common MSDF product-oriented model.[12] This presentation provides an opportunity to consider all known sets of formal rules for manipulating information as a purely abstract information-processing activity.

The roots of this interpretation may be found in the conceptual description of MSDF as an engine which ensures extraction of expert knowledge about the environment, extricating information from emitted/ reflected/ detected sensors' *signals*, through compressed/ estimated *data*, to processed and extracted *knowledge* by relational data base management systems.

This approach, proposed in 1986 and later forgotten, gives an excellent opportunity to examine the reconstruction and the evolution of information space within the last 12 years. Its internal structure has been reshaped mainly by explosive non-linear impact of the Gordon Moor's low.[13] The impact of the famous innovations of the Silicon, the global proliferation of the Net and the realization of the concept of the Mesh,[14] could be illustrated simultaneously using Arapov's 3D model. For this purpose, twelve years later we propose a new model interpretation that includes new IT achievements as shown in the table below:

Information Space Strata and Subjects ***(Information Subjects Forms)***	**Range (*Strata Scope*) $X=lgC_R$ (m)**	**Time (*Memory Potential*) $Y=lgC_T$ (s)**	**Quantity (*Multipli-city*) $Z=lgC_C$(ps)**
Signal and Data Area	**-10 ⇔ 12**	**-10 ⇔ 3**	**0**
1.Nuclear Pulse	-10 ⇔ -9	-10 ⇔ -8	0
2.Integrated Circuits (C-MOS)	-9 ⇔ -7	-9 ⇔ -8	0
3.Computer's PCB Bus (PCI)	-8 ⇔ -6	-8 ⇔ -6	0
4.Controllers and Robots	-3 ⇔ 2	-8 ⇔ -1	0
5.LAN (Ethernet)	0 ⇔ 3	-7 ⇔ 0	0
6.Electric Circuits and Systems	-3 ⇔ 6	-7 ⇔ 1	0
7.Radar and Navigation System Coverage	3 ⇔ 7	-6 ⇔ 0	0
8.WAN (Internet)	5 ⇔ 8	0 ⇔ 2	0
9.Satellite Earth Remote	6 ⇔ 8	-4 ⇔ 0	0

Sensing Coverage			
10.Direct Radio and TV Broadcast Satellite Coverage	6 ⇔ 8	-3 ⇔ 0	0
11.GPS Broadcast Satellite System Coverage	6 ⇔ 8	-3 ⇔ 1	0
12.GSM Satellite System Coverage	6 ⇔ 8	-3 ⇔ 1	0
13.Integrated (ISR, EO, IR) Sensor's System	6 ⇔ 8	-6 ⇔ 1	0
14.Space Remote Control, Navigation and Sensing	4 ⇔ 12	-2 ⇔ 3	0
Knowledge Area	**1 ⇔ 9**	**0 ⇔ 2**	**0 ⇔ 7**
1.GSM	-10 ⇔ 2	-1 ⇔ 2	0 ⇔ 7
2.GPS	-1 ⇔ 0	0 ⇔ 1	0 ⇔ 7
3.Phone (PBX)	-1 ⇔ 0	0 ⇔ 2	0 ⇔ 7
4.Man-Machine Interface	-1 ⇔ 0	0 ⇔ 3	0 ⇔ 7
5.Teletext	0 ⇔ 1	1 ⇔ 2	0 ⇔ 7
6.E-Mail	0 ⇔ 7	1 ⇔ 3	0 ⇔ 7
7.Teleconferencing	0 ⇔ 8	3 ⇔ 4	0 ⇔ 7
8.Radio Broadcasting	2 ⇔ 9	2 ⇔ 3	0 ⇔ 7
9.Interactive Cable TV	3 ⇔ 9	2 ⇔ 3	0 ⇔ 7
10.Direct Broadcasting TV	3 ⇔ 9	2 ⇔ 3	0 ⇔ 7
11.Express Post-Office Services	4 ⇔ 9	3 ⇔ 5	0 ⇔ 7
12.Office Reports and Documents	5 ⇔ 9	3 ⇔ 5	0 ⇔ 7
13.Personal Business Contacts	1 ⇔ 9	3 ⇔ 4	0 ⇔ 7
14.Daily News Papers	1 ⇔ 9	3 ⇔ 4	0 ⇔ 7
15.Post Office Service	0 ⇔ 9	5 ⇔ 6	0 ⇔ 7
16.Public Journals	3 ⇔ 9	5 ⇔ 6	0 ⇔ 7

17.Professional Papers and Journals	3 ⇔ 9	5 ⇔ 6	0 ⇔ 7
18.Scientific Papers and Journals	4 ⇔ 9	6 ⇔ 7	0 ⇔ 7
19.Science Books	4 ⇔ 9	6 ⇔ 7	0 ⇔ 7
20.Relational Data Base/Expert Systems	4 ⇔ 9	6 ⇔ 9	0 ⇔ 7
Culture Area	**0 ⇔ 9**	**3 ⇔ 9**	**0 ⇔ 7**
1.Radio Broadcast Education And Training	2 ⇔ 9	3 ⇔ 5	0 ⇔ 7
2.Cable and Satellite TV Education and Entertainment	2 ⇔ 9	3 ⇔ 5	0 ⇔ 7
3.Films and Video on Demand	2 ⇔ 9	4 ⇔ 9	0 ⇔ 7
4.Stage Art	2 ⇔ 9	4 ⇔ 9	0 ⇔ 7
5.Musical Composition	0 ⇔ 9	4 ⇔ 9	0 ⇔ 7
6.School/University Educational Program	1 ⇔ 9	4 ⇔ 9	0 ⇔ 7
7.Books	0 ⇔ 9	8 ⇔ 9	0 ⇔ 7
8.CD-ROM	0 ⇔ 9	8 ⇔ 9	0 ⇔ 7
9.Artistic Crafts	0 ⇔ 9	8 ⇔ 9	0 ⇔ 7
10.Works of Art (Pictorial, Plastic, Imitative)	1 ⇔ 9	8 ⇔ 9	0 ⇔ 7
11.Art of Command, Control and Leadership	1 ⇔ 9	8 ⇔ 9	0 ⇔ 7

Thus, we build a new structure (fig.2) named *Stratified Information Space Model (SISM).*

The comparison of the two interpretations with time lag of twelve years is shown in the table below:

Information Space Strata and Subjects *(Information Subjects Forms)*	**Range** (***Strata Scope***) $X=lgC_R$ **(m)**	**Time** (***Memory Potential***) $Y=lgC_T$ **(s)**	**Quantity** (***Multipli-city***) $Z=lgC_C$**(ps)**
1. I_S Model (1986)	**-10 ⇔ 7**	**-10 ⇔ 9**	**0 ⇔ 7**
Signal and Data Area	-10 ⇔ 7	-10 ⇔ 0	0 ⇔ 0
Knowledge Area	0 ⇔ 8	2 ⇔ 8	0 ⇔ 4
Culture Area	4 ⇔ 7	3 ⇔ 9	3 ⇔ 7
2. SISM (1998)	**-10 ⇔ 12**	**-10 ⇔ 9**	**0 ⇔ 7**
Signal and Data Area	-10 ⇔ 12	-10 ⇔ 3	0 ⇔ 0
Knowledge Area	-1 ⇔ 9	0 ⇔ 9	0 ⇔ 7
Culture Area	0 ⇔ 9	3 ⇔ 9	0 ⇔ 7

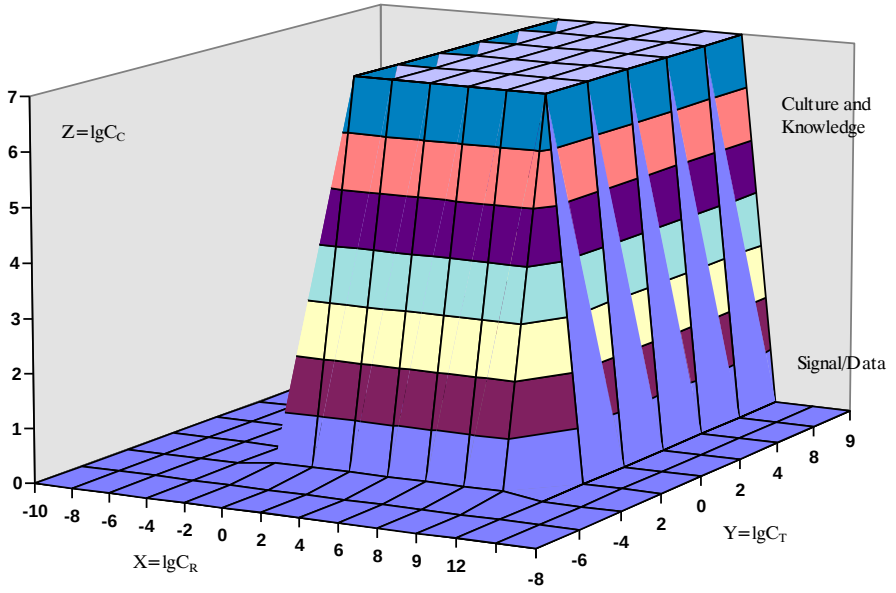

Figure 2: Stratified Information Space Model (1998)

The Examination of the differences between the two models allows to formulate basic tendencies of information space evolution at the "zero" epistemological level, as follow:

1.Culture and Expert Knowledge as products of complex processing of signals and data become the most general constituents of the Stratified Information Space Model;

2.There is a strong tendency of quantitative equalization between knowledge and culture in terms of circulation time and circulation range;

3.The information objects units (substances) which are generated, detected, filtered, estimated, transformed, transported, stored and utilized by man, are the most general information space abstractions of the products of the MSDF model;

4.The systematized sum of information space processes simulates the stream of the human cognitive process (observation, orientation, decision, and action - OODA), i.e., the cognitive human functions build on the JDL MSDF model;

5.The development of the information space subjects and their proliferation led to the Global Information Space formation, where the essence of MSDF is to extract global knowledge at the highest level of abstraction.

6.The critical MSDF technologies are related to symbol processing and knowledge engineering, which is illustrated by the significant constant "growth" of the Stratified Information Space Model at this stratum's level;

7.Within 12 years the space between Signal/Data stratum and Knowledge/Culture stratum was "compressed." The borders of the Signal/Data stratum were globally extended. As a result, today is possible to "feed" the upper Knowledge/Culture stratum with super-flow of information, which is well known as the concept of *Bitstream*.[15]

8.The development of the MSDF base technologies increase the speed of information transfer from signals to knowledge. The bottleneck today is the knowledge pre-processing and message understanding, which are not sufficiently effective to process the colossal Signal/Data upward flow;

9.The most important stratum is Culture which is under biggest strain ever experienced. The Gordon Moor's low is pushing the boarders of the Signal/Data stratum up to H.Bremermenn limit,[16] increasing the environmental "sensitivity" of the MSDF models and application tools. This environment today is volatile, uncertain, complex and ambiguous (VUCA).[17] Therefore, a new pressing lack of situation and threats MSDF models is emerging, because of new Signal/Data stratum's "consciousness" and "awareness" to environmental changes. Today's critical MSDF function, which has to be urgently developed, is "self-knowledge" or "self-consciousness" as a reflexive understanding of the internal MSDF processing states and their mechanisms. The MSDF system has to generate reasonable feed-back

sensor control and adequate knowledge base automatic adaptation to the new environmental dynamics.

10.Today's main problem in developing MSDF unified theory is caused by proponents of each stratum attempting to succeed independently as R&D supporters (*horizontally*), rather than maintaining the consensus of vertical synthesis through synergy. The resignation of the Knowledge/Culture stratum in fulfilling its paradigm-building role is the strategic paradox of contemporary MSDF R&D. It is not effective to promote particular science achievements as unified, most general MSDF vision, standing on disconnected Information Space Strata. The new MSDF understanding needs the entire energy, consciousness, and creativity of scientific community, representing all information space strata's experts.

Impact of developing MSDF technologies on Information Space

The hallmark of the MSDF theory today is the idea that chaos, nonlinearity and fuzziness of the environment are vastly unexplored. The sensitivity of new sensor and source of information suggests that strongly market oriented R&D will further improve separate Signal/Data MSDF stratum capabilities.

It is not accidental that the MSDF signal processing functions are developed today as *Space-Time Adaptive Signal Processing*. The circulation borders of the Signal/Data stratum are extremely wide and the ability for adaptation is of crucial importance for effective "sensing" and "feeling." These processing functions are often implemented with pre-processors located close to sensors and implemented as application specific hardware or as high-performance general purpose hardware, e.g., matrix processors, parallel processors, systolic arrays. Some of the main intrinsic functions assigned here are range adjustment, background subtraction, matched filtering, signal detection, signal parameter estimation, signal and clutter analysis, and track before detect.

The first stage of knowledge processing is realized on the basis of interactive multiple model or multiple hypothesis uncertainty handling adaptive *object-dependent processing*. The main functions performed here are less demanding and are often performed by a suite of processors, centralized in a conveniently-located box. These processors may be vector processors, digital signal processors, or high speed data processors. The examples here include coordinate transformation, MTT, target identification and local track fusion.

The second stage of knowledge processing functions are based on situation and threat assessment *mission-dependent processing*. These functions are least demanding and are usually performed by one or a few processors, co-located in the signal processor box. These processors are almost always standard commercial-of-the-shelf data processors. Processing examples include kill assessment, track file maintenance, track

initiation/management, intercept accuracy, communication and track handoff.

Not accidentally, the MSDF knowledge processing functions are developed today on commonly used languages and the message understanding is a rapidly advancing technology.[18] The reason is that the upper (*quantitative*) borders of the Knowledge/Culture stratum are constantly broadening. The publicity of knowledge is of crucial importance for effective "understanding," "strategic decision making," and "learning." From this point of view, all set of known man-machine interface technologies are critical, because they provide utilization of the MSDF process. On the assumption that the general MSDF model loaded into the Information space is a sum of *time-dependent, object-dependent and mission-dependent* processes, the final goal of this model utilization could be formulated as automation of all human routine intellectual activities for command and control, decision support, memory expanding, automatic learning, natural language understanding and automatic hypothesis generation.

Culture Processing is the most abstract concept related to motivation, emotion, imagination, dreaming and strategic vision.[19] This is the most important stratum's segment for strategic leadership. The processing functions at this level are being realized as expert systems, artificial neural networks, fuzzy systems, genetic algorithms, case-base reasoning systems, hybrid intelligent systems, software robots, or virtual intelligent agents. Slowly but unavoidably they form the new class of models closely related to universal intelligence.

Of crucial importance for correct understanding of Culture Processing abstractions is to perceive the MSDF as part of the unified general paradigm of computer-based intelligence. The essence of the cultural part of this upper information space stratum is that MSDF process has to acquire the essential nature of knowledge about knowledge - meta-cognitivistic knowledge.

Obviously, future MSDF technology has to be developed on the base of knowledge about the entire physical existence, i.e. the information space. The general MSDF model is ontologically incorporated in it. Today, this model is not sufficiently developed and its comprehensibility is restricted by the finite similarity of high-technologies models used and the accuracy with witch their performance is known. The similarity and accuracy levels will grow continuously and exponentially pushing the Signal/Data stratum border mainly to the *nano*- and *pico*- signals/data processing models, and enlarging slowly the Knowledge/Culture upper stratum's level. Clearly, the development of the MSDF technology will affect fundamentally the conceptual framework of information space, changing its essentials, relations and characteristics. From this point of view, this is the most fluid abstract paradigm ever considered.

It will be a misunderstanding to think that the basic purpose of MSDF concept development is to create a set of expert systems as systematic catalogues of knowledge that can be used by highly-intelligent systems. In our opinion, it will be confusing to view MSDF as theory of a particular domain or sphere of knowledge - subject matter of particular sciences. *In fact, as a comprehensive view of information space, MSDF may lay the foundation of a universal theory about it.*

Automatic MSDF as a Self-Learning System

As a result of misinterpretation of MSDF general concept and many attempts to construct such a concept based on particular formal Signal/Data and Knowledge/Culture processing models, the original objective of MSDF—to build general self-learning intelligent system—is continuously replaced by useful computer implementations of specialized customer-oriented programs. It is becoming even more clear that the MSDF projects are very expensive and the commercialization of main scientific ideas puts aside the conceptual problems. Obviously, these implementations are only tools, and the fundamental goal has to be the development of a general, self-learning intelligent system, ontologically inserted into the Information Space. Our vision is that following this direction, three main strategic goals have to be achieved in the nearest future:

- creation and utilization of a new generation high-performance signal/data assimilation computer system to achieve new intelligent sensor "awareness" and "consciousness";
- effective simulation of the human cognition process (based on new intelligent expert programs and conventional computer system), able to express intelligent behavior;
- successful development and implementation of efficient principles of knowledge extraction, processing and engineering.

Information Space chain of strata's relations *Signal-Data-Knowledge-Culture* exists in many command and control systems. However, it is very important to note the existence of massive variety of acting control feedbacks, which could be seen at all directions (vertically, horizontally, crossing, etc.). Thus, there is an opportunity to interpret the known Cyberspace definition[20] in the following way: *The Cyber-Space is the whole Information Space enveloped by automatic control feedback.* Evidently, that cyberspace is one level of abstraction up than information space. In reality, this fact could be illustrated approximately with the difference between the operational Earth Remote Surveillance (ERS) satellite system and the Global Command and Control System (GCCS).

Thus, the main information space knowledge extracted by MSDF technologies from the environment will be *reversibly* exploited from the conceptual cyberspace frame of reference for automatic command and control at personal, corporate and strategic levels.

An axiomatic fact is that all processes of nature and mind are reversible cyclical processes. Main feature of cyberspace is that it produces such reversible processes, and they are the core of its organization. The information space is totally enveloped by interrelated permanent cyclic information processing flows. The common MSDF process is linking the environment changes of any nature and any kind (both quantitative and qualitative) with knowledge about them. The cyclical reverse of these relations (in order to shape or manipulate environment) symmetrically runs the command and control feedback to connect environmental knowledge with purposeful influence to cause changes in it.

The connection between information space and cyberspace metaphors is a theme of a separate study. The considerations of this work are restricted to the abstract frame of the information space and the ontologically integrated autonomous MSDF self-learning system. In the limits of this frame ten major axioms have been formulated:

1. The information space is a network of subjects (info-systems), objects (info-carriers), information processing states, events and processes, guided by the *space-time*, *quantity-quality* and *cause-consequence* fundamental relations.

2. MSDF is a process of providing expert knowledge about environment, extracted information from emitted, reflected, filtered, detected and estimated sensors' *signals*, through correlated, associated, estimated and identified *data*, to processed in relational data bases management system *knowledge* and accumulated *culture.*

3. MSDF is the core function of the information space paradigm's model intended to:

- understand the situations and threats (concerning physical existence and mental phenomena of information space) utilizing new intelligent sensor capabilities;
- represent symbolically and linguistically its organization, structure and relations;
- evolve general self-learning knowledge base, simulate the human cognition process and extract knowledge.

4. Information potential of a given point into Information Space is the power of MSDF technology to process objects flows from signal/data to knowledge/culture which is a measure of its productivity.

5. Natural language is the main object of information space expression and its automated processing is the critical MSDF technology today for knowledge presentation.

6. Today, the information space components are interrelated at two levels forming a model of human information realm. Principal knowledge about basic aspects of this realm can be automatically extracted on the basis of universal sensor network and self-learning artificial intellect realization.

7. Information space state is a fundamental concept of situation and threat assessment, so the overall information change is the general factual term abstracted from details of various changes in the physical reality (VUCA environment).

8. As the generic event is the most common factual abstraction of the essence of the information space, so the idea of a general model of MSDF processing is formed by abstracting history, evolution, and chain of sequences of the information processing.

9. Any change in an information object is depicted geometrically into the information space as a trajectory of states. The causality of this space is represented as an intersection of two different trajectories each corresponding to a homogeneous information process.

10. The global information space structure is a sum of all local, wide-area and global information networks of different nature. To make the MSDF technology a principal framework for information processing, it is necessary to formulate the universal law of highest order into Information Space as: *MSDF is a process of knowledge extraction from sensed VUCA environment for self-learning and adequate behavioral management through cyberspace reverse cyclic feedback.*

Conclusion

Based on the formulated major principles of Information Space abstraction, the following fundamental assumptions about the impact of the MSDF technologies development on Information Space become visible:

1. All physical phenomena (electromagnetic, electrical, mechanical, thermal, radiation, etc.) and force fields (electromagnetic, nuclear, gravitational) are presented, interrelated and convertible into the information space by the MSDF general model of knowledge processing (extraction). The development of this model improves the abstraction of the information space and, thus, reversibly improves MSDF performance.

2. All processes in the information space are dependent and cyclic. The cyclical reverse of these relations symmetrically runs the command and control feedback to connect environmental knowledge with purposeful influence to cause changes in it.

3. Presently, difficulties in formalization of information space abstraction stem from insufficient conceptual foundation. The conceptual framework of this abstraction will be a semantic study of the information space which has four primary

substantives: Agentive Signals, State Descriptive Data, Event and Process Reflective Knowledge and Learning Command and Control Accumulative Culture;

4. There are four prime fundamental principles of information space states changes and evolution, categorized as: Cause-Consequence, Space-Time, Quantity-Quality and Substance-Stratum.

5. The fundamental generic structure of the Information Space is the OODA cognitive loop.

6. The Information Space is extremely non-linear network (system of systems) of subjects, objects and processes, interconnected by the ontological network of cause-consequence fundamental principles through self-learning intellect.

Notes:

1 This work presents results of the project "*Information Warfare and its MSDF Philosophy*," accomplished at Bulgarian Academy of Sciences, 1995-1997.

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