DEVELOPMENT OF THE CONTROL BASED ON THE BIOLOGICAL PRINCIPLES

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Abstract

Nowadays, because of the continuously increasing the load and flight envelopes, the aircraft are flying in very complex conditions close or near the critical regimes. Therefore the aircraft control must use the latest results of the sciences and technology, like MEMS technology making possible to develop principally new controls. This lecture deals with the development of a new control based on the biological principles. A new method uses the aircraft position sensing, velocity measurement, balance- and visual-based control. The control is synthesized as a modified neural network. The lecture makes overview on the aircraft control development, discusses the way of human sensing and thinking and describes the new biological principle based control developed.

1. Preface

First airplanes were design for 1g load and there were used in clear weather conditions, only. However, in 1908, 80 % of licensed pilots were killed in flight accident [1]. In 1910, E. A. Sperry invented the gyroscope, which he used first in stabilization and steering of ships and only later invented in aircraft control [2]. The Wright brothers had been worked for a long time on the better stabilization of their airplane and finally, in 1911, Orwill Wright introduced first automatic control devices applied on his airplane.

Principally, for 1940's all the critical flight regimes had been described and analyzed, as well as the stability, maneuverability, controllability including classical automatic controls had been basically developed. Later the modern and even so called post-modern controls were introduced. However piloting becomes more and more complex (Fig. 1.).

There is a new question: what is the more important the handling qualities or the carefree handling. So, how can we make control that could be closer to the human way of thinking and actions.

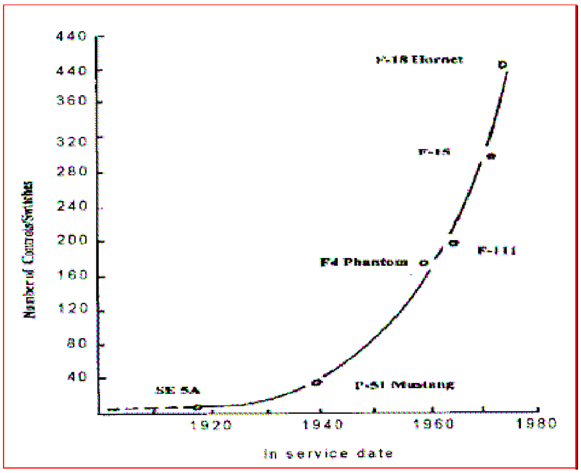

Fig. 1. Increasing the number of controls and switches per crew member [3]

2. Introduction

Nowadays the applied control methods are very vary from simple feedback control through the adaptive, robust, feed forward, fuzzy, neural network based controls to the nonlinear and stochastic controls including the voice, eye-based, etc. controls, too. All these methods can be characterized by features of the sensors and actuators as well as determining the control commands.

The latest technology - as MEMS technology based micro gyroscopes, micro cameras, micro sensors and actuators, smart structures, etc. - make possible to develop the new control philosophy applying the biological principles.

Some developers working on such programs (general biological principle-based controls, or vision controls, only) use the quit complex methods of data processing. For example in vision based control they try to calculate the three dimensional positions of the image elements. However for example the eye of the fruit fly (Fig. 2., 3.) is thus roughly equivalent to a 26x26 pixel array covering one visual hemifield [4], which is ridiculously low compared to state-of-the-art artificial vision, and about 150 000 times „worse" then human eye retina. It means, we can find much more simple solution for vision control, and the biological concept-based control generally can be realized on the simplified basis.

If the fruit fly so success in flight with use of such eyes "made from very limited sensing elements", then technical system constructed with use a better sensing elements may use for full automatic flight control and the human having really much more better sensing organs must learn to flight better then it has solved for today. It is not problem of the ergonomics, not problem of the ergatic systems (systems including the human in loop as the one of the element having special characteristics); it is a new problem for developing the integrated and intelligent systems.

Therefore the way of human sensing and thinking must be studied and integrated into the control systems.

This lecture deals with development of a new biological principle based control. A new method uses the aircraft position sensing, velocity measurement balance- and visual-based control. The control is synthesized as the modified neural network. The lecture makes overview on the aircraft control development, discusses the way of human sensing and thinking and describes the new biological principle based control developed.

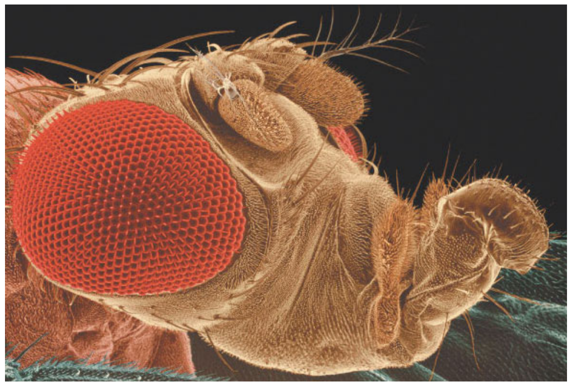

Fig.2. Fruit fly eye (http://www.nature.com/nature/journal/v431/n7009/images/431635a-f1.0.jpg)

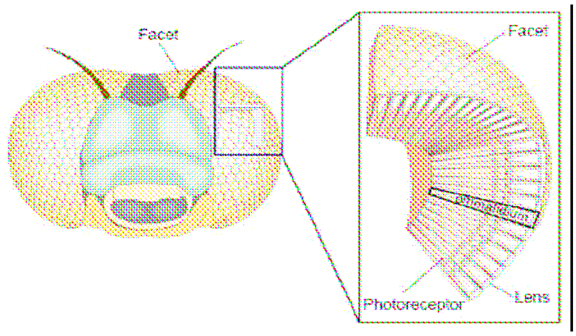

Fig.3. The compound eyes of flying insects
The compound eyes are made up of repeating units, the ommatidia, each of which functions as a separate visual receptor. Each ommatidium consists of a lens (the front surface of which makes up a single facet), a transparent crystalline cone, light-sensitive visual cells arranged in a radial pattern, and pigment cells which separate the ommatidium from its neighbors. (Figure is taken from [4] that adapted it from http://soma.npa.uiuc.edu.)

3. Flight control goals and tasks

Principally, the goal of the aircraft control can be defined shortly and simple: it is making the flight safe and controlled with minimization of the unwanted deviation from the planned and designed flight modes, flight trajectory [5]. Such ability of aircraft is characterized by handling qualities.

In reality the aircraft control is a much more complex problem solving of which required knowledge in many different areas [1, 6]: basic and aeronautical sciences, control theory, informatics as well as the other related sciences (systems engineering, innovation theory, management, etc.).

Complex problem of aircraft control, as usually, is divided into many sub-problems like shown in Fig. 4. So, the control used in solving the problems of stabilization, handling characteristics, maneuver characteristics, loading constraints, controllability reserves, minimum drag, flight modes and flight path optimization, gust elimination, structure load and life management, increasing the flight and load envelopes, automatic limitation, avoiding the critical regimes, control on critical regimes, departure problems, recovery problems, etc.

The controls of civil and military aircraft (especially the fighters) are considerable different. In case of civil aircraft the handling qualities, avoiding the critical regimes and optimizations are the most important tasks. However, in case of control of military aircraft the maneuver characteristics, flight mode optimization, increasing the flight and load envelopes, control on critical regimes, solving the departure and recovery problems are very important, too. Therefore a new term, "carefree handling" was introduced mostly to military aircraft control design. It means the reliable limitation of commands from a trained pilot in order to keep the aircraft always inside the allowed envelope, to avoid departure, and to prevent overloading of the aircraft and unconsciousness of the pilot [1]. The carefree handling technology was started with use of simple autopilots through stick shakers/pushers. In autopilot mode, the pilot has only limited command authority, "the computer flies the aircraft". The modern technology can provide fully automatic control including the control of recovery from dangerous situations. That means, today, the control deals with the co-ordinated motion of centre of gravity of aircraft, too, while 20 years old control realized and realizes the co-ordination for rotation around centre of gravity, only. So, in the carefree mode, the computer is only monitoring and limiting and "the pilot flies the aircraft". Because the high complexity of the fully automatization of the control, often an aircraft is only carefree with respect to some critical parameters.

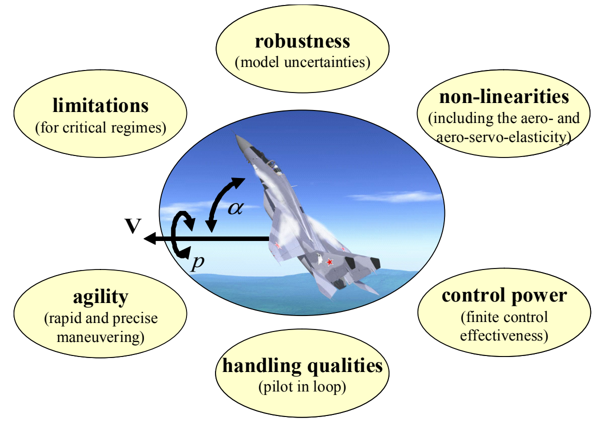

Fig. 4.: Mean tasks and problems of aircraft control (drawn with use of ideas from [7].

The effective carefree handling characteristics allow the increasing the mission success, full concentration of the pilot on the target, applying the command inputs in a more aggressive manner, while using the full flight performance, reducing the risk in man – machine interaction, reducing the structural load factors, etc. On the other hand, the development of the carefree handling more expensive because the additional software and testing and using this technology reduces the aircraft agility, and confuses some pilots like to have the full control in hands.

The carefree control deals with load factors (load factor rates), too. The modern carefree handling characteristics are implemented in a quadruplex digital flight controller without mechanical backup that makes aircraft carefree for any configuration with respect to departure and violation of the boundaries of some characteristics including the load factor, too [1].

4. Control methods – alternative controls

With checking the references it is seems too many - thousand and to sands - control methods have developed for last 30 years. The huge number of papers indicates that no unique or best method was found. So, there are no general approach, general methods to be recommended for defined cases. Plus to them, the development process of the real aircraft (flight) control is the much more complex task, needs knowledge in many different areas (as it was figured earlier) and large experience. So, the control law design needs the senior control designers having „tacit" knowledge in aircraft control law development process.

The history of control theory (Fig. 5.) can be divided into several periods characterized by the followings [2, 5]:

- pre-classical control:
  - use of the practical control devices (e.g. control surfaces on the aircraft),
  - development of the models and investigation technologies (linearized models of aircraft motion, stability investigation, basis for frequency based tools, Nyquist criterion; operator methods; transient response),
  - development of the early automation and remote control,
  - works on the three-terms: proportional-integral-derivative;
- classical control:
  - frequency based tools, stability via gain and phase margins,
  - mainly useful for SISO (single - input – single - output systems - one channel stabilization),
  - still most applied as simple feedback control;

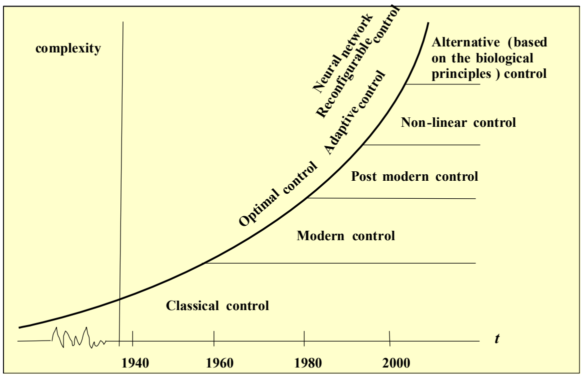

Fig.5. Control methods

- modern control:
  - applying the state space approach to linear control,
  - developed for SISO and MIMO (multiple – inputs – multiple – outputs systems),
  - performance and robustness measures are often made explicit,
  - introduces the linear optimal control, linear system theory, nonlinear extensions, adaptive control, etc.
- postmodern (sometimes called as robust or neoclassic) control:
  - generalizes ideas in classical control to MIMO systems,
  - uses the operator theory at its core, but can be easily interpreted in frequency domain;
  - flexible uncertainty representation, system identification, optimal control and filtering, more general optimal control with mixed norms, etc..

In history of modern and postmodern control there are some new methods that introduce the considerable development in the control theory and practice, like

- optimal control (application of maximum principle and optimization to linear and nonlinear systems, extension of LQ theory to infinite-dimensional systems, use of adaptive methods),
- robust control (developing for systems having uncertainties),
- nonlinear control (working out the special control techniques for nonlinear systems),
- fault and failure tolerant control (including the fault and failure detection, and reconfigurable control),
- carefree control (especially developing to modern highly maneuverable aircraft for making automatic limitation near critical regimes),
- control of motion of c. g. of aircraft (for solving the recovery problems),
- alternative control (introducing the new controls based on the biological principles),
- distributed control (that will develop control system applying the distributed MEMS and nano technologies),
- intelligent control (that uses the soft computing, fuzzyfication and neural network for developing artificial intelligent "co-pilot" or fully automatic pilot systems).

The alternative controls [3, 5]. i.e. voice recognition, helmet, head, eye, biopotential and gesture sensing try to include the human operator into the control loop as the active element with taking into account the individual possible features. An another step to biological principle based control is made by artificial intelligence control, that was started with using the fully automatic control of small aircraft models by using the vision-based control (Fig.6.)

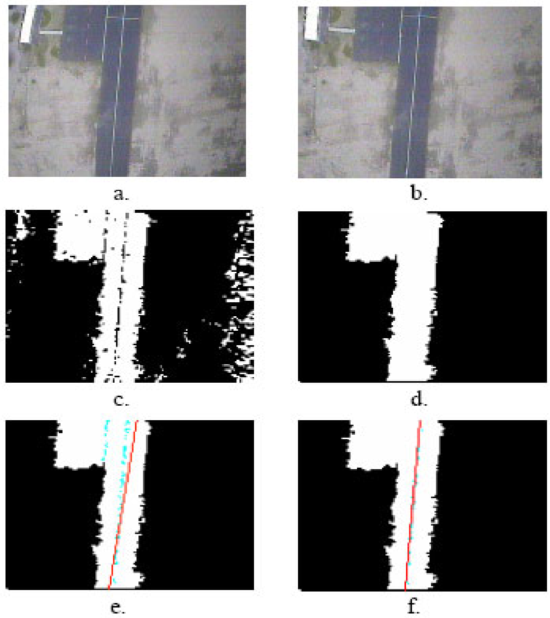

Fig.6. Example op vision-based control [8] uses the road detection algorithm (a.) original image, b.) corrected for distortion, c.) Bayesian pixel classification, d.) Connected-component analysis, e.) hough transform, f.) least-trimmed square line fitting)

5. Sensing organs

A human as "biomotoric system" uses the information provided by sense organs for determining the motoric actions. The mean element of the "system" is the nervous system working partly automatically.

Human as intelligent system applies its brain [9] for "detailed data processing" of information coming from sense organs including the analysis of sensed information, reasoning, synthesis of control principles, supporting decisions for motoric organs. The process has some special characteristics like learning, adaptation, memory, etc.

From piloting point of view the balance may most important from the human sense organs [10] (Fig.7.). (As it known, the pilots are flying with use their "botty" for sensing the aircraft real position and orientation in space.)

The sense of balance [10] is maintained by a complex interaction of visual inputs (the proprioceptive sensors which are affected by gravity and stretch sensors found in muscles, skin, and joints), the inner ear vestibular system, and the central nervous system. Disturbances occurring in any part of the balance system, or even within the brain's integration of inputs, can cause the feeling of dizziness or unsteadiness.

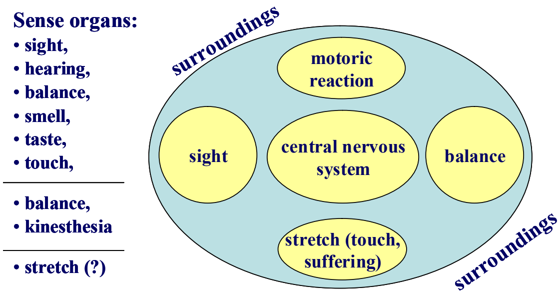

Fig.7. Human sensing organs

In addition to this the human has an another sensing, kinesthesia [10] that is the precise awareness of muscle and joint movement that allows us to coordinate our muscles when we walk, talk, and use our hands. It is the sense of kinesthesia that enables us to touch the tip of our nose with our eyes closed or to know which part of the body we should scratch when we itch. (Some scientists are really thinking about that, the future aircraft control system must be operated by thumbs because the new generation has trained them on the "Game Boy".)

6. Thought

The human activities are controlled by human brain that is the anteriormost part of the central nervous system in humans as well as the primary control center for the peripheral nervous system.

The human brain [9] is a very complex system based on the net of brain cells called as neurons that specialize in communication. The brain contains circuits of interconnected neurons that pass information between themselves.

The neurons contain the dendrites, cell body and axon. In neurons, information passes from dendrites through the cell body and down the axon.

Principally, transmission of information through the neuron is an electrical process. The passage of a nerve impulse starts at a dendrite, it then travels through the cell body, down the axon to an axon terminal. Axon terminals lie close to the dendrites of neighboring neurons.

When the nerve impulse reaches an axon terminal it causes the release of a chemical (called a neurotransmitter) that travels across the gap (the synapse) between a terminal and the dendrite of the neighboring neuron. Neurotransmitters stick to receptors in the neighboring dendrite and trigger a nerve impulse that travels down the dendrite, across the cell body, down the axon etc. Our behavior is the consequence of millions of cells talking to each other via these chemical and electrical processes.

The brain controls the involuntary activities (heartbeat, respiration, and digestion) and conscious activities (thought, reasoning, abstraction, decisions, memory).

There are about 10^{14} connections in the human brain and possible each one holds a byte of memory. Each neuron makes or can make about 1000 calculations per second. So, the human brain may perform about 10^{17} calculations per second.

From technical point of view Kohler defined two different approaches applied for description of the thinking (knowledge) [11]:

- Topographic thinking: the nervous system is operating as the simple net, in which the connections are defined everything (deterministic model)
- Dynamic thinking: there are the time depending and energy transfer processes in the nervous system.

For reproducing the human way of thinking in technical systems, we must understand the brain operation as the „natural computer". Of course the brain and computer are the absolutely different „systems". The different can be understood, if we return to some works and definitions of Touring and Neumann.

Turing created his known Turing machines [12] in 1936 that can be characterized [13] as there are the:

- kind of state machines (at any time the machine is in any one of a finite number of states, because
- everything can be given in form of algorithms (if not, then that is not interesting), however
- all thing which can be given in algo, that can be solved in finite step forms (abstract algebraic automat)
- with technical development it becoming harder to make different between the artificial intelligent and human.

On the other hand Neumann defined the differences between the artificial and human thinking, between the computer and nature that are including in followings.

- sizes (neurons are mach more smaller),
- the neurons are working on more complex basis (context dependence),
- the machines are deterministic – human thinking is statistic,
- the machines use the digital principles – nervous system applies the analog processes, too.

The conventional artificial intelligent uses the information strongly in syntactic way, while the meanings of the inputs are not investigated.

The human way of thinking is the intentional, because the human thinking has an intended direction, well, or not so clearly defined goal.

Another important different between the artificial intelligence and human is the intuition, i.e. thinking in case of incomplete information knowledge. (It is important to understand, the intuition is not instinct characterizing the animals.)

The human mind as a complex process can study not so easy. It may the recognition process is most investigated. It is depend on the goals, objects and situations [15]. However, the process is simplified, limited and much intended as it shown in Figure 8. This is a process, which is modeled well, too (Fig. 9.), and can help in developing a new control methods based on the biological principles.

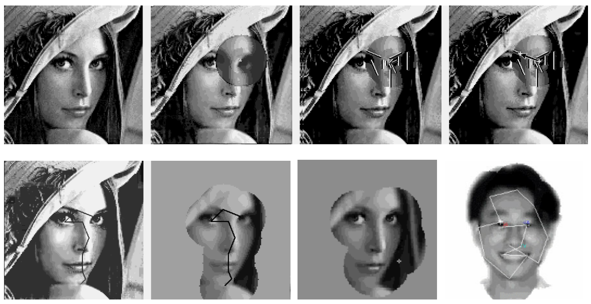

Fig.8. Recognition process [15]

Such vision recognition is really very interesting process as it can be understood from pictures shown in Figure 10. For making decision that somebody is happy enough to check camber of mouth. Even, the camber of something like “mouth” can govern us to make a special decision about the happiness.

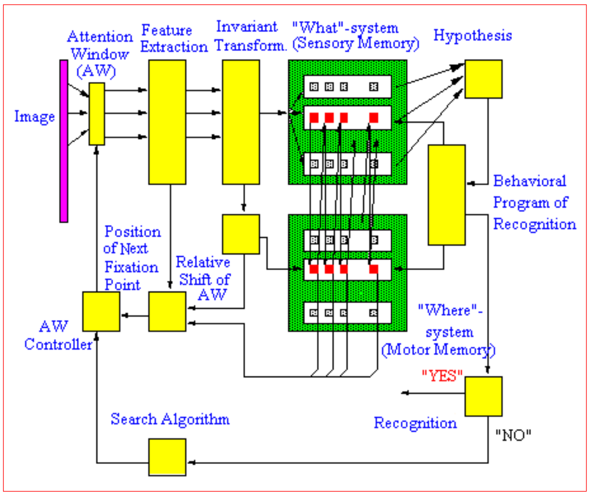

Fig.9. Model of human vision and pattern recognition [15] (it is treated as a biological function modeling both eye motion and image processing)

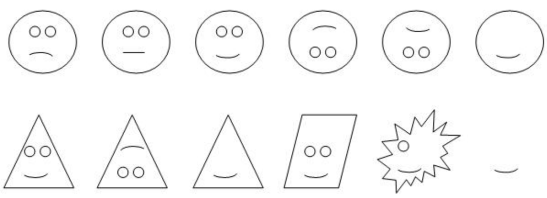

Fig.10. Recognition of the happy “man”

In Summary, the human thinking is characterized by

- syntactic and semantic processing of the sensed information,
- working on the basis of the large net of small and simplified articles (neurons),
- using the complex system oriented approach,
- making parallel thinking and activity,
- learning (synthesis of the new knowledge),
- model-formation and using the models (including verbal models applied in learning processes and complex mathematical representation),
- long-term memory,
- tacit knowledge (took in practice),
- intentional thinking (goal and wish),
- intuition (subconscious thinking),
- creativity (finding the contexts),
- innovativity (making originally new minds, things),
- unexpected values can be appeared,
- jumping from quantity to quality.

7 A new control philosophy

With accordance to our investigation on the biological based sensing, reasoning, decision making we have made three major conclusions:

- vision recognition uses a very simplified method targeting the recognition of the mean element from its form “measuring” and “monitoring” its changes,
- the pilots are piloting the aircraft with use of balance sensing,
- using a brain for analysis of sensed information, situation awareness (reasoning) and decision support.

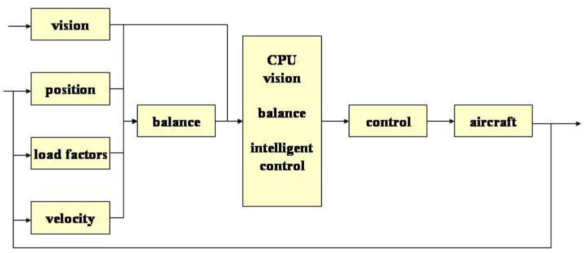

Fig.11. A new principle of developed control

Applying these three conclusions, we can defined a new control philosophy (Fig.11.) based on the biological principles. Novelty of this new control philosophy is included into

- using the balance sensing as the important input for control,
- integrating a special vision- and balance-based control into one system, and
- using a special central law based on the modified neural network.

The first, using the balance sensing results can be realized easy with applying the mathematical model in which the load factor (acceleration) components are included into the state vector.

The general model of aircraft motion can be written in the continuous/discrete form as follows [5, 16, 17]:

$$\mathbf{x}(t_0) = \mathbf{x}_0 \ ,$$

$$\dot{\mathbf{x}}(t) = \mathbf{f}\big(\mathbf{x}(t), \mathbf{u}(t), \mathbf{p}(\zeta)\big) + \mathbf{F}(\mathbf{p}(\zeta))\mathbf{n}(t) \ ,$$

$$\mathbf{y}(t_i) = \mathbf{g}\big(\mathbf{x}(t_i), \mathbf{u}(t_i), \mathbf{p}(\zeta)\big) + \mathbf{G}(\mathbf{p}(\zeta))\boldsymbol{\eta}_i \ .$$

Here **x, u, p, n, y, η** are the state, control (input) and parameter (structural and operational characteristics), state noise, observation (output), and measurement noise vectors, **f** and g are system state and observation functions, **F** and **G** are system matrices, t is time and ξ is the random value. Principally **u** is determined vector from the different between the intended and estimated (from measurement) state vectors. However **p** is unknown vector depends on the real flight situations and it can be changed randomly and non-continuously that is figured by random value, ζ depicting real position of the parameter vector, **p** in its possible space, Ω_p .

As usually, the state noise vector is assumed to be zero-mean, white Gaussian, and stationary; and the measurement noise vector is assumed to be a sequence of independent Gaussian random variables with zero mean and identity covariance.

A second feature of the new system is associated with use of vision-based control together with balance-based control. The vision-based sub-system uses the

- vector field calculation (Fig.12.),
- horizon detection (Fig. 13.), and
- "hole detection" (Fig. 14.).

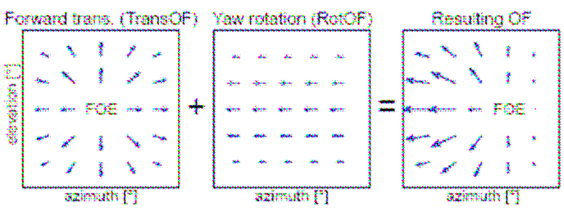

Fig. 12. Translational and rotation vector fields determined from images [18]

In this case, the "hole detection" is a real new element in the system. As it can be understood from Figure 14., in autonomous control, as control of UAV, the aircraft has to fly to the clear direction, that can be detected as white hole in images.

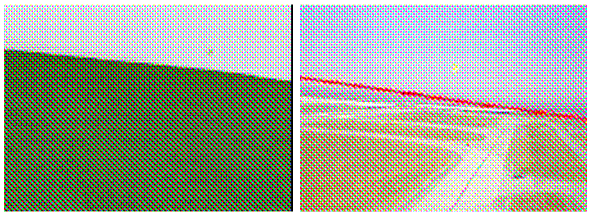

Fig. 13. Horison detection [19]

Fig. 14. Hole detection (chematic example)

Finally, the modification of the neural network system tries to take into account the specific features of the human thinking.

In general case the neural network is based on the method shown in Figure 15.

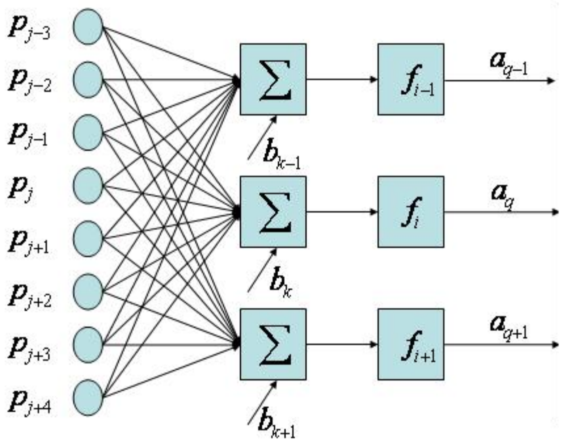

Fig. 15. Neural network

Here the output **a** is generated with use the measured parameter inputs, **p**, and bias, **b** :

$$\mathbf{a} = \mathbf{f}(\mathbf{wp} + \mathbf{b}),$$

where **f** is the vector transfer function and **w** is a waiting matrix. Such network before its application must be trained for defining and identifying the transfer functions, waiting coefficient and bias.

Of course the output can be applied as input into the second neural network as it is shown in Figure 16 taken from MATLAB manuals

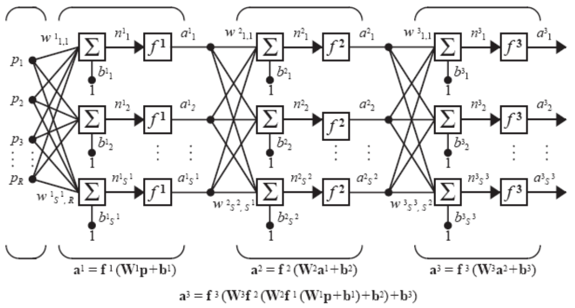

Fig. 16. Multi- (three-) layer network

With accordance to our study on the human sensing, reasoning, decision making, the conventional neural network model has been modified as it shown in Figure 17. A new philosophy is based on the completing special numbers from output vector **a** determined by neural network for defining the actions (control commands) required from table of data. This table of data represents the special features and long term memory of developing system.

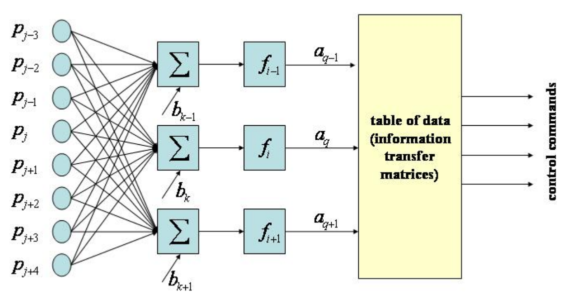

Fig. 17. Modified neural network

8. Practical studies

During development of the new control philosophy we organized practical investigations on the two different levels. At first, the pilot workload and pilot actions were studied in the flight simulator. For example, we have measured the pilot eye motions (Fig. 18.).

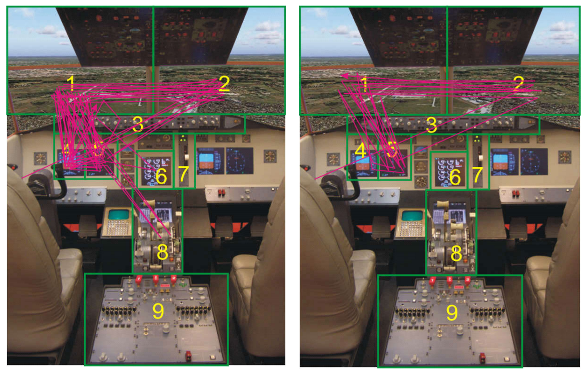

Fig. 18.: Eye movements (gaze directions) of the pilot during landing and turning

A radio controlled small aircraft model (Fig. 19.) developed at Department of Aircraft and Ships, BUTE was applied in another practical investigation. The goal of this flight measurement is the collection of inputs for training the neural network developed.

Fig. 19.: Model applied in flight tests

According to our investigations the newly developed control has considerable advantages in simplify, and accuracy. However planned flights tests have not fully realized, yet.

Conclusions

The Department of Aircraft and Ships at the Budapest University of technology and Economics has initiated a long term research for developing a new control based on the biological principles. First results of this project are outlined here. The mean conclusion can be formulated as follows:

- we need new ideas for increasing the flight and load envelopes areas,
- the modern, post modern controls deal with strongly nonlinear and robust stochastic systems,
- the control in nature quit different from technical one,
- important to take into account the human sense „technology",
- a new control system under developing based on the biological principles,
- three major novelty of the new control are the
  - using the balance sensing as the important input for control,
  - integrating a special vision- and balance-based control into one system, and
  - using a special central law based on the modified neural network.

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