

Prediction diagnostics for system reliability

MIRKO NOVÁK

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1. Introduction

Each day people have to interact with many various systems of different nature. This concerns everybody, without exception. The differences can be in the nature and type of these systems and in the role which in such interactions a particular human subject plays and, of course, there are differences in the conditions of the interaction.

Nevertheless, in all cases we are very interested if the particular system under consideration operates well, and more over, if one can expect its successful operation also in the future (or under other changed operation conditions), i.e. if the system is reliable.

This concerns also the telematic and transportation systems. The interaction with them consumes a significant part of almost everybody's activity.

Through all of its history, mankind has fought in general with the problem of the man's interaction with various systems and also with the reliability and safety of these interactions.

Under the term system we understand a certain ordering of real or abstract objects (system elements or functional blocks, sometimes also subsystems) arranged so that as a whole they can realize some required external system functions (activities). (D 1)

Systems can be generally divided into two groups:

- Natural systems, and
- Artificial systems.

Under natural systems we shall understand living organisms, their groups and communities, but also non-living systems present on Earth and in the universe, such as the weather, wind, river flows, sea waves, sea streams, the solar wind, radiation level etc.

Artificial systems are those created by man, mainly by his intentional actions.

Both these two kinds of systems interact, very often in a complicated manner. They interact of course also with the man, either as an individual or as a group or the whole community or mankind.

In all cases where we meet the natural and/or artificial systems, we strive for the least problematic interaction, to predict the behavior of systems with a high degree of reliability, and for the systems which we have created to operate as we wish.

With regard to these artificial, by us created systems, we wish to keep the number of their system faults minimal and the deviation ΔF of their system functions F from their expected values as small as possible.

We are also interested in a maximal duration of this acceptable state, or, more generally, in the maximal range of independent variables P , in which it is valid.

In other words, we are interested in the maximal functional reliability and life-time (life-range) of a system.

The functional reliability has therefore to be considered one of the most important factors specifying the practical applicability of any real system. An arbitrary system, though having excellent properties and power, will be of very low practical use if it functions well only exceptionally, under conditions that are not well defined, and its operation record has many faults. Also the expenses of keeping the system in operation, if they are not proportional to the system's value and power, can significantly diminish its real value.

In general, very high operation reliability and a very long life-time belong to highly desired properties of almost all real systems. Moreover, we usually require that the particular system not only itself operates well, but that its operation does not have any negative influence on the function of other systems operating in its neighborhood and also not on any human subject or human community with which it interacts.

These requirements are often included in the concept of system safety. Nevertheless, among the aspects of system safety is often included also the particular system's resistance against disturbing influences, caused either by operation mistakes of the human crew or by somebody's ill will.

The tendency to construct systems with a high functional reliability and safety has been known for a long time. Originally, it was projected into the philosophy that very reliable systems have to be constructed first of all from very reliable parts. Though this design philosophy is evidently not wrong, sometimes it can lead to unrealistic and expensive solutions. Therefore, also other design philosophies for construction of highly reliable systems are developed. There are four fundamental principles:

Besides the previously mentioned usage of very reliable components with a long life-time, one can also use the philosophy of system (or some its parts) sparing, or the philosophy of minimization of system function sensitivities on the values of system parameter changes. These three approaches have been known and used for

many years. The last approach, developed and used in various applications only recently (the first works in this respect appeared at the beginning of the 90s), can be based on the concept of the so-called prediction diagnostics (see e.g. [1] to [8]).

2. General Aspects of System Reliability Theory

2.1 System structures

In this paragraph we shall deal with the basic concepts of system reliability, safety and life-time and other significant factors influencing the values in real systems. We shall discuss the properties of amorphous, homogeneous and heterogeneous systems, their alliances and also whole networks of alliances. The higher structures appear to have been the focus of interest especially in the last few years as a theoretical tool capable of describing the properties of some higher artificial complexes, appearing in some areas of human activity, namely in transportation (but also in medical care, in defense, large scale economy etc). We shall deal with analysis and optimization of their fundamental properties and respective limitations. We shall classify the complexity of elements, from which the systems and higher complexes are constructed and we shall speak about aspects and possibilities of the homogenization of principally heterogeneous systems, which very often involve in many structural places the parts acting as human factors.

In general, complexes can be classified according to their complexity into the following structural levels:

- Functional blocks,
- Single systems
- System alliances,
- Networks of system alliances.

In relation to this hierarchy, below the level of functional blocks one can place the level of simple elements, but even though they are of very high importance, we shall deal only marginally with them here. This is because the aspects of reliability, which are the main focus of this whole part of our book, project onto this hierarchical level mainly into technological considerations, while here we concentrate on system structural and functional point of view.

The requirements on satisfactory high and often maximally possible reliability (and therefore also safety) of the complexes with which we have to deal, use, control and interact, are of fundamental significance for all mankind, not only from the economical, but also from ecological and safety aspects.

The prognoses of global development of our Earth (made recently especially by the so called Club of Rome and many others – see e.g. [9], [10]) which were especially discussed in a very interesting book [11] concern also the problems of reliability. Though the book [11] is now already 14 years old, many of its ideas are still valid.

In the last few years such aspects have been discussed by authors of frequently appearing contributions presented namely in Scientific American – (see e.g. [12] to [15]). The theory of system alliances was discussed for example in [16] to [19].

From all of these, one can summarize that high requirements on system reliability and safety represent a non-neglectable part of the set of factors which the human society must realize in the near future, if it is to have hope of reasonable survival. This fact concerns all the above mentioned hierarchical levels of system structures, but in general its level of urgency is proportional to the size and complexity of the respective systems.

To be able to discuss fundamental problems, however, the term system and other higher levels of mentioned structural hierarchy are to be understood more precisely as

any organized set of physical, chemical, biological, social and information components, parts, elements, which are able to realize one or more rational functions **(D2)**

(This sentence can-not, however, be considered the definition of system – it is more of a free characteristic).

As systems in the sense of (D2.1) are considered not only sets of technical, namely transportation parts, components, blocks and subsystems, but also those arrangements and complexes forming commercial, economical, military and medical and others equipments and tools. However, for simplicity of expression, we

shall speak later on often just about systems, meaning by this term also the above mentioned higher hierarchical levels.

Each system has certain basic characteristics. Among them one has to point out especially:

- The set of realized system functions $F = \{F_k\}_{k=1, \dots, K}$,
- System structure (topology) St ,
- Set (vector) of system parameters $X = \{x_i\}_{i=1, \dots, N}$,
- Set (vector) of independent variables $P = \{p_j\}_{j=1, \dots, J}$.

These characteristics and their relation to the considered system are shown schematically in Fig. 2.1.

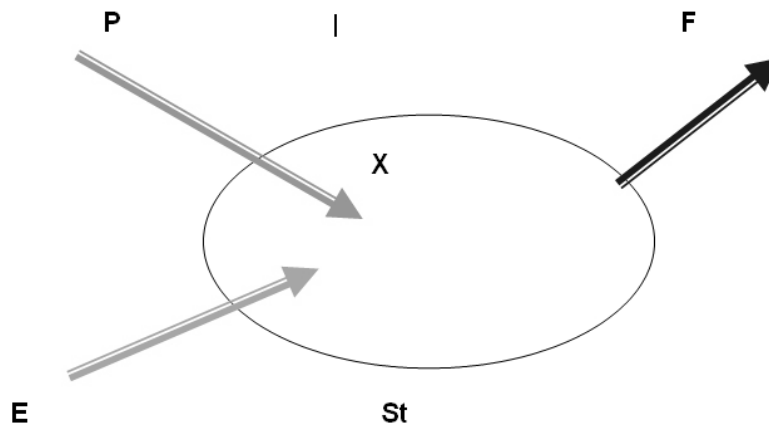


Fig.2.1 General system and its basic characteristics

These four system characteristics can be taken as basic or primary.

The system structure St and the vector of system parameters X can be considered internal system characteristics, while the set of system functions F which it realizes and the vector P of independent variables can be called external system characteristics.

To these basic system characteristics can in certain cases also be added the set of environmental functions E , in which the influence of system functions of other system functions, realized by other systems, is interacting with the one under consideration¹).

Besides these primary characteristics, also a set of secondary system characteristics has to be considered. Among them, the

operation reliability H^2), the

life-time L and the

safety B

are to be considered.

Sometimes can be added to secondary system characteristics also

- readiness,
- resistance to faults,
- reparability,
- consumption of energy,
- power efficiency,
- functional, production or economic yield,

¹ However, sometimes the environmental influences E are considered part of the vector of independent variables P .

² In English literature, reliability is usually denoted by the letter R . However, because this letter we use here for denoting a region in the space of system parameters X , the letter H was chosen for reliability.

- system mass,
- system dimensions,
- system price etc.

Some of them and their significance are discussed in more detail later on.

Suppose now that for a certain system its structure St is known and that it consists of N system parameters x_i , $i = 1 \dots N$, the values of which can be represented by real numbers.

The system's stage can be represented by the position of the parameter vector $X = \{x_i\}$ in the N -dimensional space $\{X\}$.

Under the influence of independent variables P and/or the environmental influences E the position of the vector X in the parameter space $\{X\}$ changes and the vector X moves along a certain trajectory Ψ , which we shall call the life-curve of the system.

The trajectory, its shape and size represent the behavior of the system.

Later on properties of $\Psi(P)$ will be discussed in more detail.

Certain components of the vector P of independent variables can have a different physical significance (to those belong usually the temperature, humidity, illumination and/or radiation level, etc). However, time t needs to be considered first of all, because it is the only absolutely independent variable, whose speed and direction of flow we can neither change, nor stop.

In any case, we must consider

$X(t)$ for all the i , $F(t)$ for all the k , and also $St(t)$.

However, very often also the dependences

$E(t)$ and also $H(t)$, $L(t)$ a $B(t)$ are to be taken into account.

Let us denote further:

F_0 the required (nominal) values of system functions, of the system under consideration,

ΔF are the acceptable deviations of actual values of these system functions from their required values.

The system can be considered operable if

$$F - F_0 \leq \Delta F \quad (1)$$

Here the minus sign is the distance between F and F_0 in the K -dimensional space $\{F_k\}$, measured by the appropriate metric. Of course, if F is scalar, the minus sign in (1) is a simple algebraic operation.

Let us now turn our attention to system structures St .

It was already mentioned that each system (except the extremely simple one, called amorphous, which consists of one component only and has no internal structure) can be decomposed to a certain set of partial functional blocks FB_i , $i = 1 \dots s$,

$$S \equiv \{FB_i\}_{i=1 \dots s}.$$

For amorphous system $s=1$.

However, in majority of cases one has to deal with systems of $s \gg 1$.

Suppose that we deal further with these cases only.

With respect to the nature of partial functional blocks from which the system is formed, we distinguish:

- homogenous systems where all the partial functional blocks are identical, i.e.

$$FB_1 \equiv FB_2 \equiv \dots \equiv FB_s, \quad (2)$$

- heterogeneous systems where the identity (2) is not valid.

The majority of systems belong to the second category.

Of extraordinary importance are heterogeneous systems and among them those where interaction with the human subject plays a role. These will be considered in further chapters of this part of the book.

Hybrid systems are a special case of heterogeneous systems, in which the partial functional blocks of different physical nature are used.

2.2. Structures of heterogeneous systems

Each heterogeneous system S consists of a certain number N_s of partial functional blocks FB_i , $i = 1, \dots, N_s$, which mutually interact. The individual functional blocks FB_i can differ regarding their structure, complexity and function and also, in the case of hybrid systems, their physical nature.

In principle, all functional blocks can be divided into the following three groups:

- Operational (working) functional blocks,
- Auxiliary functional blocks,
- Junction functional blocks (interfaces, synapses).

To the first group belong the blocks which realize certain, even partial system functions of the system.

We consider the information system e.g., such to those belong the processors and memories before all.

The second group is formed by functional blocks for power supply, safety, reserves switching, diagnostics and repair, etc.

The third mentioned group of functional blocks is of extraordinary importance, because these functional blocks ensure the information transmission among all other functional blocks forming the particular system, their interaction and cooperation. In simple cases the interfaces can be reduced to direct connection of inputs and outputs of functional blocks, however, in most cases, the successful information transfer requires also a certain information transformation and translation, which is realized by interfaces.

In Fig. 2.2 an example of a simple heterogeneous system is shown.

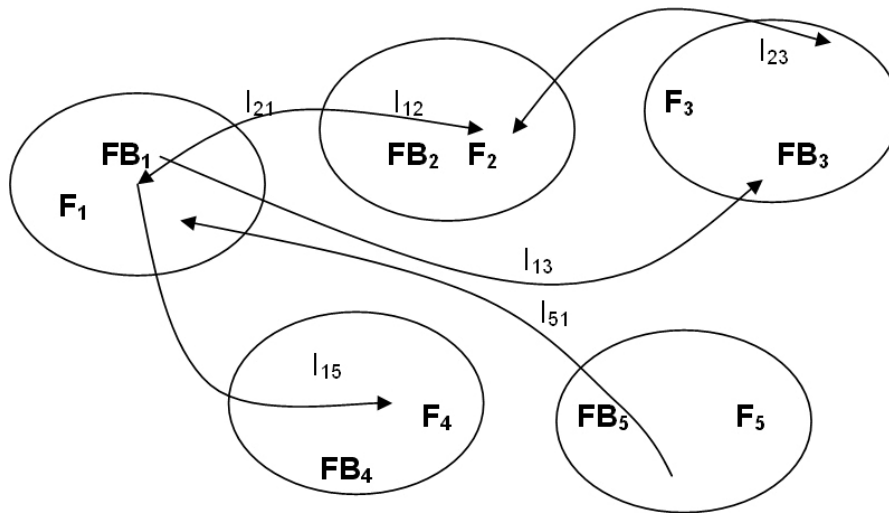


Fig. 2.2 An idealized example of a heterogeneous system

Here $N_s = 5$ mutually interacting operational functional blocks FB_1 to FB_5 were considered. These realize a partial set of transfer functions F_1 to F_5 and partial interactions I_{ij} .

In this schematic figure, the auxiliary functional blocks and interfaces are not drawn.

Each from the respective sets of partial system functions is formed by k_0 functions F_{nk} , therefore

$$F_n = \{F_{nk}\}.$$

These partial system functions F_{nk} are realized above the parameter space X_{nk} of individual system parameters x_{nkj} , which can be J_{nk} dimensional.

Suppose without loss of generality, that all the partial system parameters have only real values.

In all the considered space X_{nk} one can find a certain region R_{Ank} for which it is true that, if a certain vector of system parameters is x_{nkj} inside R_{Ank} , the respective system function F_{nk} does not deviate from required values F_{nk}^* more than allowed, i.e.

$$F_{nk} - F_{nk}^* \leq \Delta F_{nk} \text{ pro } X_{nk} \in R_{Ank}^1 \quad (3)$$

If the considered system S operates well, all the respective functional blocks FB_i also operate well, i.e. it is $X_i \in R_{Ai}$ for all i.

It is evident, that this requirement is necessary, if for the operation of the system the simultaneous operation of all its functional blocks is needed, but that it is not satisfactory.

If the interaction among the partial functional blocks is considered, one has to take into account also the reliability of all partial interaction functions I_{ij} .

Suppose now, without restriction of generality, that all the considered functional blocks forming the particular system S are mutually connected and that none of them is functionally isolated. The direction and sense of these interactions are expressed by the interaction functions I_{ij} which express the transformation of the set of system parameters X_{Oi} (signals, transformation media etc.) from input ports of blocks FB_j on corresponding sets of parameters X_{Ij} , acting on input ports of blocks FB_j interacting with them. In such interactions also the corresponding interfaces can be considered.

Suppose further that under certain conditions a situation can arise that:

- - there appears a fault of some system function F_i or F_j of mutually interacting blocks FB_i and FB_j ,
- - there appears a fault of some interaction function I_{ij} .

In the case a) one or more trajectories $\Psi_{Fi}(t)$ approaches dangerously to boundaries of R_{Ai} , resp. R_{Aj} or it even crosses it.

In the case b) a similar situation appears with regard to the trajectories $\Psi_{Ii,j}(t)$, representing the life-curves of interacting functions I_{ij} in the region of acceptability $R_{A I i,j}$ in the space of parameters of this interaction.

Solving the problems of analysis (and the subsequent optimization, or prediction diagnostics) of the heterogeneous systems reliability requires first of all the knowledge of the whole set of $\Psi_{Fi}(t)$ trajectories of system functions, resp. the life curves $\Psi_{Ik}(t)$ of the interaction functions. For the solution of this task several numerical methods exist (see [1] e.g.). Some of them will be discussed later on.

However, the analysis of the respective regions of acceptability R_A is the primary task. Unfortunately, because the number of considered system parameters N is often quite high, the respective analysis of R_A in the corresponding multi-dimensional space can require a lot of numerical computation. One also has to face the problem of uncertainty, if one supposes that certain parameter values can be estimated only with limited accuracy. Therefore it is recommended to use a reasonable model of the system under consideration, chosen as an acceptable compromise between requirements of model accuracy and the need for its simplicity.

The design of a reasonable model represents a very serious problem. If too simplified a model is chosen, one could achieve an acceptable simplification of the necessary analytical procedure, however, the results can be of low accuracy. If too complicated a model is chosen, not only is the analysis difficult, but also the results can be loaded with such high inaccuracy that they are completely false.

The choice of the appropriate accurate system model, if inaccuracy in its parameter values is considered, requires experience and skill.

One possible way how to achieve a reasonable model complexity consists in the use of the fact that not all from the n_k system parameters on which a certain system function depends have the same influence on its values. The dominant parameters in this respect are those which have the maximal values of respective system function sensitivities. Therefore it is recommended to analyze the sensitivities S_x^F first of all. From the subsequent laborious analysis of regions of acceptability and life curves trajectories all the parameters can be excluded whose sensitivities are low enough. The same approach can be used also when dealing with interaction functions.

Therefore, we try to deal only with a simplified set of primary parameters of the system under consideration, which we call the set of significant parameters.

However, sometimes it is useful to complement the introductory analysis of system parameters X also by the analysis of hidden correlation among the x_i components (eg. by methods of data-mining) and select some

¹ As we have already mentioned, the – sign can be here considered in the algebraic sense only if all the respective partial system functions are of scalar nature. In the opposite case it must be interpreted as the distance in corresponding spaces, measured by the appropriate metric.

limited number of derived, so called secondary, parameters, representing the hidden correlations. These secondary parameters complete the set of significant parameters.

3. System Operation Reliability and Safety

Human society suffers from various system failures, accidents and catastrophes caused by them.

The influence of such events has been felt through history, however, their significance increases with the size of human population in general and with its density in particular parts of the world.

Today, regional catastrophes as the December 26, 2004 earthquake near Sumatra or Hurricane Katrina can cause the death of several thousands up to hundreds of thousands people and tremendous financial losses.

Accidental or catastrophic events appear usually almost unexpected and people are not prepared to face them. This fact usually multiplies the losses.

Human society therefore must be, if it is to behave rationally, extremely interested in maximal obtainable systems and system alliance operation reliability and safety. (Theorem 1)

Each system or systems alliance activity is realized in some space of its system functions F_k , $k = 1 \dots K$.

The size of the space F and the maximal values of the partial system functions F_k characterize the significance of the particular system. This concerns especially the power of the system outputs, their economic aspects and the number of people who have to deal with it.

There exists some dependence $f_{n-s} = d(|F|)$ between the average frequency f_{n-s} of non-standard situations of operation or interactions with the considered system (or system alliance) and the size $|F|$ of this space F .

Fortunately, this dependence $f_{n-s} = d(|F|)$ is usually inverse proportional. It can be modeled in various ways, but the best is probably the hyperbolic model, i.e.

$$f_{n-s} = c_0 + \frac{c_1}{(|F| + c_2)^{c_3}} \quad (4)$$

where c_0, c_1, c_2 and c_3 are real, empirically determined constants, which influence the shape and the position of the hyperbole (Fig.3.1).

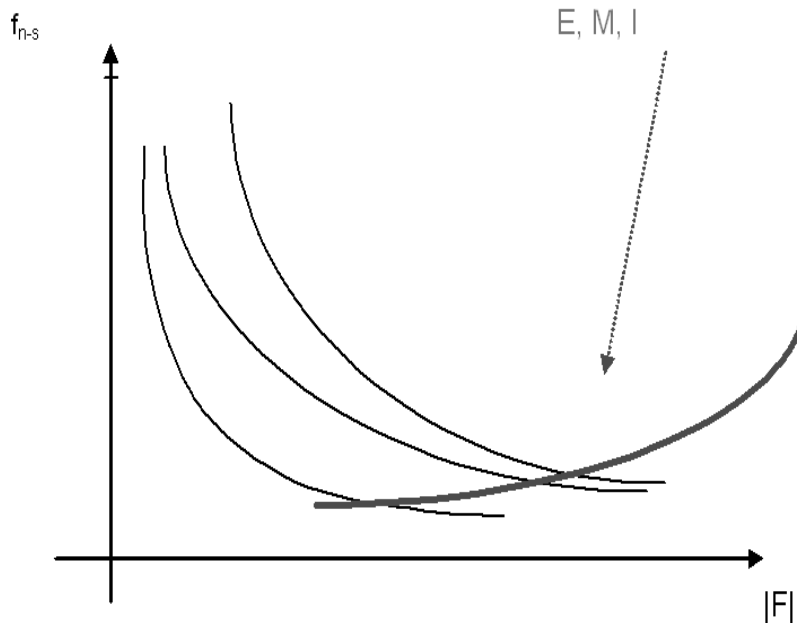


Fig. 3.1 Hyperbolic model of the dependence between average frequency of nonstandard situations f_{n-s} and the size $|F|$ of the space F . The green line represents here the size of the energy E , mass M and information I with which the respective system or alliance deals.

This means that the non-standard situations appearing in operation of really significant and powerful systems come much more rarely than in the case of simple, cheap and in many copies existing systems.

Of course, the hyperbolic model is only one of many other inverse proportional models which can be constructed. Even though it is very simple, the estimation of the constants $c_{0,1,2,3}$ can be quite laborious.

To find realistic values of $c_{0,1,2,3}$, the analysis of the frequency of appearance of non-standard situations has to be made in a considerably long history of operation of the considered system. This is evidently a difficult condition to fulfill, because usually the respective data are not fully at our disposal and if so, they can be disturbed by various sources of imperfections. For newly constructed systems or system alliances, historical data are not at our disposal at all and need to be replaced by data sets coming from investigation of other similar cases.

Moreover, the two-value classification of the system operation ability which was considered above (system operates well – it is in a standard situation, and system does not operate well - it is in a non-standard situation) often does not represent realistically enough the actual situation. Later on we shall discuss the possible situations, falling in-between these two limits.

Nevertheless, in any case, the systematic recording of all relevant data representing the system parameters, in which or among which the information of non-standard event in system operation can be hidden, is extremely important. The creation of the respective data-base is therefore necessary both for dealing with all systems, for which the size of $|F|$ reaches a certain limit or which exist in high enough number M of its copies. As the figure of merit of necessity, the product

$$M * |F|$$

can be taken.

One has also to take into account that all parameters $c_{0,1,2,3}$ of all non-standard situation frequency appearance models are usually influenced by the vector of independent variables

$$P = \{p_j\}, j = 1 \dots J,$$

especially by the time $P = t$.

Therefore, the validity of some particular model is limited to a certain region R_P of independent variables P .

The analysis of system operation failures and resulting accidental and catastrophic events shows that only *very rarely they appear absolutely without any preceding signals*.

Such signals can be of course very weak and hardly recognizable, nevertheless, a careful and systematic use of sophisticated analysis of data (mainly in the form of time-series) gathered from various sensors gives the hope that the **advent of particular nonstandard situation can be detected**.

Though it is often very difficult to predict the advent of system operation failures and eventual accidents and catastrophes, our present knowledge of

system theory,

system reliability,

signal analysis together with

modern computer,

sensor and

communication technology

open the possibility that at least something can be done.

3.1 Prediction diagnostic

The main tool for preventive activity is to develop and use the methods of predictive diagnostics, which allow – if well used – not only to:

indicate the danger of a particular system or the whole system alliance failure,

but also

to estimate the probability of an event,

to predict the time in which this could happen

and the optimal ways for the event's prevention or, if this is not possible, for optimal restoration and compensation of losses.

The whole created set can be called the marker set of the system which together with the respective characteristics of relevant structure forms the basis for a simplified system model, useful for further analyses.

Let us now focus on two significant cases of heterogeneous systems.

The first concerns systems where the interaction functions among partial subsystems are so significant that when some fault in a certain partial functional block appears, the whole set of cooperating functional blocks is affected. These systems can be called systems with strong internal interaction coupling.

The second case represents systems where some functional blocks come in operation repeatedly, several times. These systems are called systems with repeated internal interaction coupling.

In all heterogeneous systems, at the junction of a partial interacting functional block the respective information is transformed and translated. This activity, realized by respective interfaces, has to be included in the respective interaction function (see Fig. 3.2).

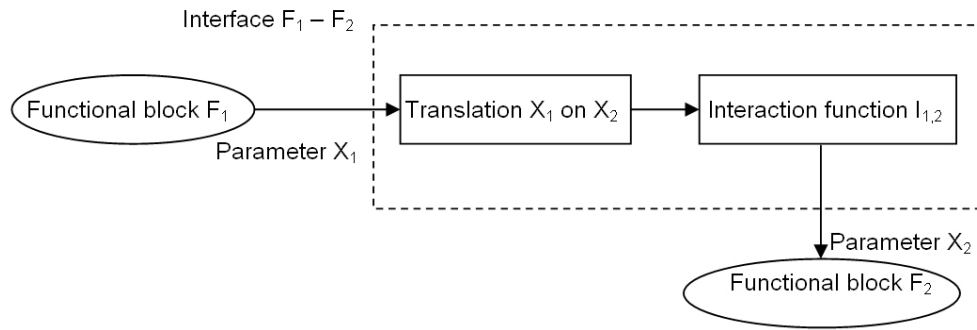


Fig. 3.2 The translation between blocks F_1 and F_2 .

Output parameters of one interacting functional block must not correspond with input parameters of the second functional block and so they have to be translated and mutually matched.

The influence of interaction function is projected in changes of input parameters of the following functional block and therefore also in its life-curve shape. The not-fully reliable translation of information in such an interaction can lead to significant changes of the following block operation reliability.

It is evident that in both mentioned types of systems, with strong internal interaction coupling and with repeated internal interaction coupling, the faults in interface information translation can cause significant faults.

3.2 Hybrid systems

Hybrid systems are the product of interaction between at least two partial systems (functional blocks) having different genetic codes and only one identity value. Therefore, they are also heterogeneous.

The traditional concept of hybrid system, whose dynamics is defined in continuous and eventually partially discrete time, involves the discrimination of at least two corresponding, often hierarchically structured system levels.

The concept of hybrid system does not bring for the main part of transportation and communication applications any significant advantages, because it does not reflect that type of heterogeneity which is most significant for application (see [16, 17] e.g.).

In the field of system engineering the extended definition of a system, which seems to be suitable for our further consideration, is presented (see [16, 17, 18, 19]).

Its three-component definition is

$$S: (A, R, \gamma), \quad (5)$$

where A ($A_1, A_2, \dots, A_n$) is the set of system parts (elements) identified on a certain identification level. To these parts belong functions F ($f_1, f_2, \dots, f_n$). R is the set of interacting parts identified by a common interface. γ (gamma) represents the targeting of processes resulting from chaining the pairs from R .

This definition can be further extended by M , δ and I , where M is the magnitude (generalized size) of the respective system, identified by the number of processes that can be realized in it, δ is the process from M , which identifies the processing type of the considered system (in analogy with the genetic code of a living organisms.) A model of identification δ is the table:

function of part A partial process M	f_1^x	f_2^x	f_3^x	...	f_n^x
p_1	/	/			
p_2	/	/			/
$\vdots$					
p_m	/		/		

in which symbols x represent the so-called strong functions, / represent the participation of a particular function on process chaining.

It is evident that the process p_2 identified by formula 1,1,0,...1 can be the genetic code of the system. Finally, I is a symbol for the identity of the system, appearing in three layers:

- Internal cooperation of system parts,
- Support of processes δ
- Acceptance of target behavior (external interface) of the system with its environment.

The extended definition of the system has therefore the form

$$S: (A, R, M, \gamma, \delta, I) \quad (6)$$

The process of construction of the identity (5) is discussed in [16] to [19].

The hybrid system (HS) is then defined as the integration of at least two partial systems of the type (3.3) having different genetic codes and one common value of identity.

One can denote it as

$$HS: (A_i, R_i, M_i, \gamma_i, \delta_i, I) \forall i, \quad (7)$$

where i is a natural number.

The expression (7) is the definition of a hybrid system, whose presentation can be constructed according to the kind of its homogenization, the integrity of the whole, existence in the environment, structuring of the whole and dynamics of the whole with respect to the environment.

One can distinguish the following levels of homogenization:

- technological level, consisting in reaching acceptable regions of system parameters and parameters of interfaces.
- macro-physical level, which can be also seen as the level of balancing the interaction with the environment.
- biological level, involving the aspect of occupation of the environment.
- social level, in which the homogenization on the base of communicated information dominates, with special regard to used languages.

Languages of system parts, or languages of partial systems forming system alliance, or of the network of system alliance, can differ in grammar and in semantics. The nature of the information exchange between such system complexes can be significantly multilingual, both with respect to the individual system parts or the environment. The necessary homogenization can be achieved by translations in the multilingual space. The reliability of translation and its speed are markers of translation quality and also of homogenization. The integrity of the whole is ensured by translation completeness.

It can be proved that on the level d) of homogenization all the previous levels are included. It is therefore in that respect universal.

This is the reason why in analyzing hybrid systems the language representation is preferred. This implies the necessity to define alphabets and syntactic forms in all languages used in all partial components or subsystems of the system or system alliance.

The operation reliability and safety of complex system operation depends therefore in general first of all on the reliability and safety of the fourth mentioned level of its homogenization. As a significant tool for achieving the maximal possible improvement of procedure reliability, the methodology of prediction diagnostic has to be mentioned.

The basic principle of prediction diagnostics consists in

- formulation of requirements of respective system or alliance properties,
- determination of the set of its parameters, which dominantly influence its behavior and functional properties,
- estimation of the system and/or alliance parameter development under the influence of independent variable changes,
- prediction of the horizon of these changes where the parameter vector approaches (or breaks) the boundaries of regions of acceptable parameter values (regions of acceptability)
- recommendations for preventing or minimizing the changes of the respective system (or alliance) parameters or structure, the danger of boundaries breaking.

These 5 steps of prediction diagnostics often overlap and can also be solved at least partially in parallel.

In any case, the application of prediction diagnostics requires a deep understanding of a good part of system analysis theory, of signal theory, and a lot of numerical computing.

Recently developed methods of prediction diagnostic were, however, designed mainly for systems (and eventually system alliances) which were relatively simple (N and K below 10).

However, many contemporary applications (e.g. in neuroinformatics, in flight control, in human-machine interactions and advanced methods of system operators – drivers, pilots, dispatcher – training, etc.) force us to deal with much more complicated systems where the numbers K and/or N reach the order of several hundreds and more.

Moreover, the parameters of the systems or system alliances are often significantly correlated, their correlations vary with change of acting independent variables (namely with time) and the values of these parameters are determinable very often only with considerably high uncertainty.

For such cases the methods of prediction diagnostics have to be modified significantly.

In further sections of this part of our book some related aspects are discussed in more detail.

4. Brief survey of conventional prediction diagnostic methodology

For successful realization of the prediction diagnostic procedure, the following partial knowledge and information is necessary:

- knowledge of an accurate and efficient analyzable system (or alliance) model
- knowledge of regions of acceptable parameters of the model
- knowledge and tools for prediction of the system (or alliance) life curve
- knowledge of possible system (or alliance) faults and their restoration.

Let us now briefly discuss the main aspects of these four areas.

4.1 System (or alliance) models

The necessity to have at our disposal a reasonable system model applies to all theoretical dealings, either in the field of analysis or of synthesis. The vague word “reasonable” has to be taken in the sense of accurate enough for describing the main important properties, but not too complicated, for that would cause problems in calculation. Very simple models can suffer from omitting some important system properties and vice versa, very accurate and complicated models can cause problems of low transparency, difficult determination of model parameters and high requirements on computing power necessary for performing the analysis.

Also the factor of natural inaccuracy of model parameter determination plays a much more significant role when dealing with a very accurate, but also very complicated model. The so called “golden” empirical rule of relations between model complexity and allowable tolerance of its parameter values says that the number of model parameters N and maximal tolerances τ of its parameter values have to be inverse proportional, i.e. that for example in the case of N=100 the tolerances of these 100 system parameters should not be higher than $\tau = 1\%$.

The choosing of the right system (or its parts, functional blocks, elements) mode belongs to the art of system analysis. We can mention McCulloch-Pitts model of neuron as an ingenious example which, though it was

published already in 1943 and is very simple, still represents the fundamental tool for dealing with neural networks and is widely used.

The system parameters could be of various nature, but one has to prefer the real ones, either continuous or discrete.

4.2 Investigation of regions of acceptability

The parameters x_i ($i=1 \dots N$) of the system model form the N dimensional system parameter space X , which can be either of continuous or discrete (or combined) nature.

Each realization of the system (or alliance) can be represented in this space by the system parameter vector X .

All the existing realizations of the system (or alliance) appear in some area of this space, called the region of deviations RE which is a part of the usually larger region RP called the region of possibility involving all the points in X , in which theoretically the vector X can appear.

The properties of the the system (or alliance) depend on the position of X in X . These properties can be expressed by the set of K system or alliance functions $F \{F_k\}$, $k=1 \dots K$. To the nominal or required system properties F_0 belongs the nominal position of system parameter vector X_0 .

Of course, the actual system properties can differ from F_0 , which is usually the case. If the deviation of F from F_0 is not larger than allowed, the system (or alliance) can be deemed acceptable. Here one has to say that the specification of the allowable deviations ΔF of F from F_0 is, in general, not an easy task.

The decision whether some system can, under certain conditions serve well or not can represent quite a complicated problem with a high degree of inaccuracy and fuzzy aspects.

Nevertheless, all the system realizations whose actual system functions F do not deviate from F_0 by more than ΔF have their values of system parameter vector inside some region of X , called the region of acceptability RA .

If X remains inside R_A , the respective system performs well and its F is not distant from F_0 more than allowed, i.e.

$$F - F_0 \leq \Delta F \quad (8)$$

One has to note that in (8) the symbol $=$ has to be taken as the distance in a K -dimensional space measured by the appropriate metric.

As it was already mentioned, the analysis of the shape and size of regions of acceptability of system parameters X in the parameter space X is one of the primary tasks of system reliability optimization.

Before we discuss the respective methods of R_A investigation, we shall try to formulate some main problems:

Suppose that we deal with a deterministic system, the actual functional properties of which can be determined from the knowledge of its structure St , its values of the vector of system parameters X and of the value of the vector of independent variables P .

As independent variables we take those which influence system properties, but whose values are not dependent on our will. Time t is a typical independent variable. Of course, also some other independent variables can be taken into account, such as the temperature, humidity, solar radiation level, etc., but **time t is the only one whose flow we cannot influence and stop.**

Suppose further for simplicity that the structure of the considered system does not change with independent variables. This means that the tool for analysis of the system function values depend only on X and P , so we can put down

$$F = F(X, P) \quad (9)$$

Note also that in some cases, especially when dealing with more complicated systems or alliances and with whole networks of alliances, this assumption need not be valid.

If this is so, one has to consider the respective dependencies of the system structure on independent variables, namely on time t , and modify in the corresponding manner the functional expression of F .

Suppose further, that the necessary analytical tool for determination of the values of F is at our disposal and that we are able to realize the necessary analysis with satisfactory speed, accuracy and efficiency.

This assumption of is of a high importance, because, as it will be shown later, very often the procedure of the system properties analysis (i.e. the determination of system function values) has to be performed many times for various values of X and P.

Let us suppose also that to certain nominal values of the vector parameter components x_{i0} also correspond the nominal values of the system functions F_{k0} and moreover that the requirements for the maximal allowed deviations ΔF_k of each system function F_k from its requested value F_{k0} are known.

The fulfillment of this later assumption is sometimes considerably problematic, because the sharp limits of acceptable properties of the system are not known in all cases. Quite often, such limits of acceptable system operation are more or less fuzzy and there can be discussion whether it can still be safely used or not. Therefore, as we have already mentioned, the clear and sharp formulation of ΔF is a serious and difficult problem.

Now we are able to formulate several basic tasks from the system tolerance theory:

a) to find for a given nominal system parameter vector X_0 and given ΔF the optimal set of parameter deviations Δx_i so that the inequality (9) holds and that the production yield Y of multiple realization of respective systems will be of maximal value.

b) Here the production yield can be expressed as

$$Y = \frac{\int_{R_C} \Phi(X) dX}{\int_{R_E} \Phi(X) dX} \quad (10)$$

where $\Phi(X) = \{\varphi_i(x_i)\}$ is the probability of the appearance of the values of the vector X inside the region R_E of allowable deviations of vector X components (if correlations are not among the considered vector X components, the R_E has the form of an hyper-rectangle with sides Δx_i and $R_C = R_A \cap R_E$.)

to find for a given nominal system parameter vector X_0 and given ΔF the optimal set of parameter deviations Δx_i so that the production cost $C = C_{\text{const}} + C_{\tau}$ is minimal, where the C_{τ} is the sum of all costs of components, depending on tolerance values and C_{const} the cost of components or production operations which do not depend on parameter tolerance (i.e. packaging, surface covering, shipping, etc).

$$\text{Generally, } C_{\tau} \text{ can be approximated as } C_{\tau} = \sum_{i=1}^N \left(\alpha_i + \frac{\beta_i}{\tau_i^{\gamma_i}} \right) \quad (11)$$

where $\alpha_i, \beta_i, \gamma_i$ are empirical constants.

$$\text{c) suppose further so called } \underline{\text{well-designed}} \text{ system, i.e. that } X_0 \in R_A \quad (12)$$

with the provision, however, that this design of the system has an introductory character only and that we are really interested in a design which allows to achieve (besides fulfilling the fundamental requirement (12)) also either the minimal production price or the maximal system operation reliability. This is the so called task of "design centering" (this name originates in the fact that if the respective region of acceptability can be approximated by a hyper-sphere, the resulting position of the centered vector X_C should be moved with respect to the X_0 towards the center of R_A . Actually, the point R_C should be placed so that around it the largest region $R_E \in R_A$ can be specified and that the total price of the whole production C_M of M pieces will be minimal. Here

$$C_M = M C^{\sim} + \sum_{t=1}^T \sum_{i=1}^N \frac{\beta_{it}}{x_{it}^{\gamma_{it}}} M_{E_t}, \quad (13)$$

$$\text{where } C^{\sim} = C_{\text{const.}} + \sum_{i=1}^N \alpha_i \quad (14)$$

is the sum of all the production costs, independent of the tolerances of the parameters x_i , M is the total number of all the realized systems, M_{ET} is the number of system realizations, for which the $X \in R_{ET}$, $t=1 \dots T$ and T is the total number of tolerance groups, β_{it} and γ_{it} are empirical constants, specifying the relations

between the partial price C_i and the x_{it} projections of R_{ET} on the axes x_i (such a situation is presented for $N=2$ in Fig. 4.1.)

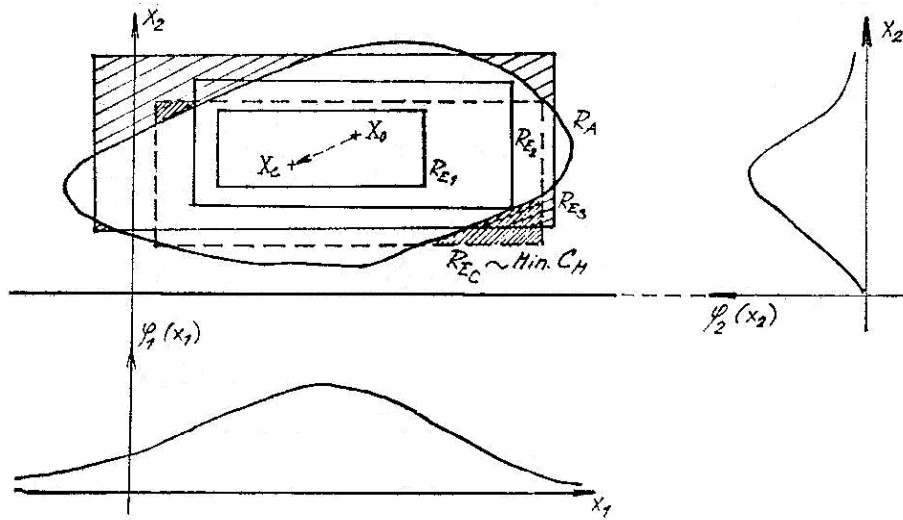


Fig. 4.1 To the production price optimization

In recent years a lot of effort has been given to its solution. The result is that at present we have several methods for its solving at our disposal.

In both previous cases we did not consider the possibility of the use of the so-called production wreck, i.e. of products which, though not fulfilling the condition $X_m \in R_A$, can be repaired or restored so that after the well performed restoration procedure they can be used as well as the good pieces. Of course, for optimal price considerations also the price of the restoration procedure must be taken into account.

Let us now consider a simple system, composed from components x_1 and x_2 , i.e. $N=2$. Analyzing the possible relations of the respective R_E with respect to R_A , one can distinguish several basic situations.

In Fig.4.2 this is shown schematically.

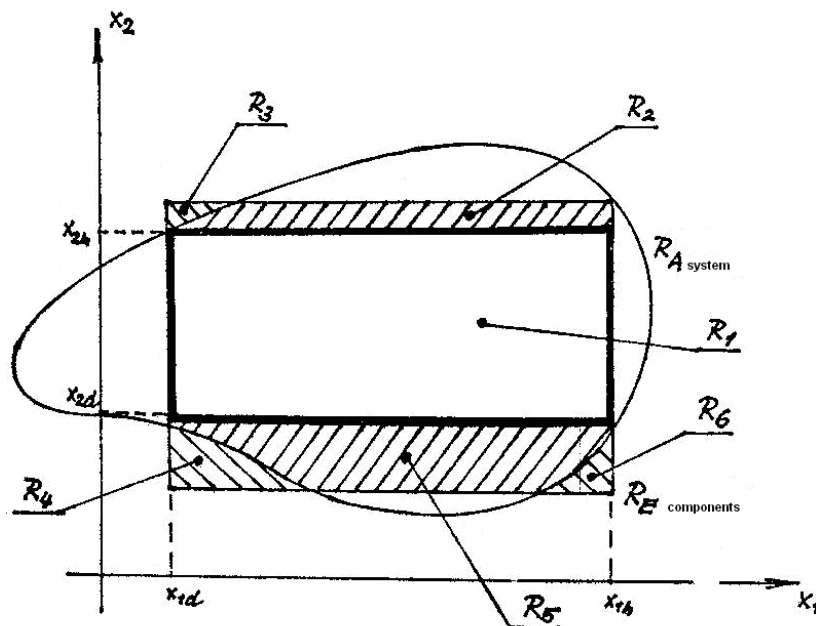


Fig.4.2 Possible relations between R_E and R_A

We see that from the total production of system component of parameters x_1 and x_2 , corresponding to a certain region of acceptable deviations R_E we can compose a certain amount

$$\int_{R_1} \phi(x) dx$$

of well operating systems.

After that there remain a certain number of systems with component parameters x_1 and x_2 , corresponding to

$$\int_{R_2} \phi(x) dx,$$

$$\int_{R_3} \phi(x) dx,$$

$$\int_{R_4} \phi(x) dx,$$

$$\int_{R_5} \phi(x) dx,$$

$$\int_{R_6} \phi(x) dx,$$

from which one can find a certain number of combination of parameters x_1 and x_2 so that the corresponding vectors X lie inside the regions R_2 and R_5 , which are inside the R_A . So we can obtain an additional well-operating realization of the respective system. Such optimized choice of R_E with respect to certain R_A , so that with additional combination of system components in the primary production selected as not acceptable, is sometimes called the problem of component tolerances pairing and it is an important tool for production yield maximization.

In the previous discussion we did not consider the possibility to exploit components whose system parameters are outside the region R_1 which is specified by the inequality $x_{id} \leq x_i \leq x_{ih}$ for all i . The applicable region of deviations, defined in this manner is, however, sometimes too small and therefore one is interested in their extension, even if the inequalities which it defines can be much more complicated.

Suppose that each interval of deviations $\Delta x_{ij}=1 \dots N$ is divided into several subintervals. Then the suitable choice of combining of these subintervals can lead to the requested extension of useful regions of parameter deviations. An example (drawn here also for the simple case of $N=2$) is shown in Fig. 4.3.

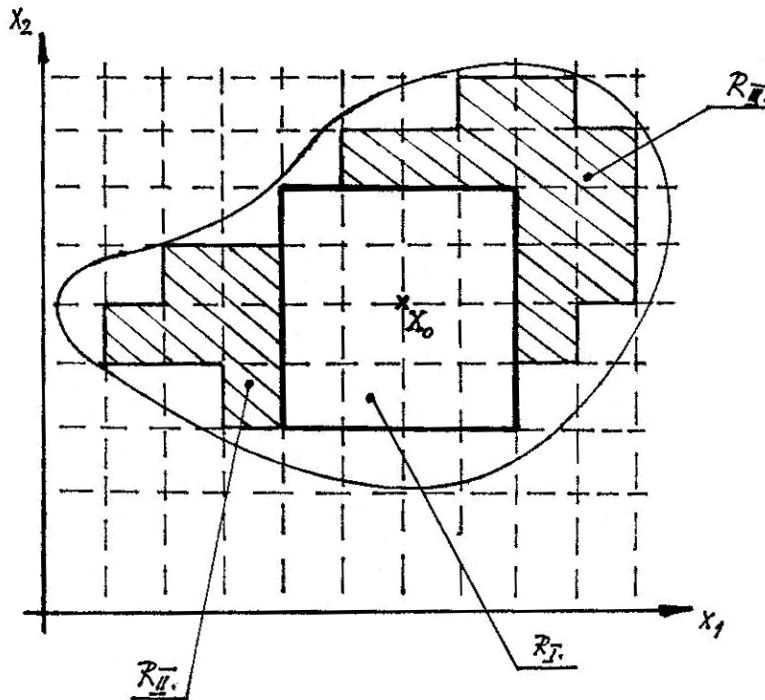


Fig.4.3 Subintervals in R_A

The original region R_I is subsequently extended by sub-regions R_{II} , R_{III} , etc., and therefore the region of acceptability R_A is approximated step by step.

Till now we have considered situations which can be called static, i.e. we have not respected the possible influences of independent variables – from which group time is without any doubt the most significant.

Let us, therefore, now consider the cases where

$F = \{F_k\}_K = \{F_k(X, p_j = t)\}_K$, when some or all the system parameters are more or less influenced by time.

If the system properties for a static case is in the space X characterized by the position of the vector X , in these, let us say dynamic cases, the already mentioned trajectory $\Psi(P)$ plays this role, called also the respective system life curve.

This is the trajectory, which follows the vector X in the course of changes of the independent variable P .

If $\Psi(P)$ remains inside R_A , the system is able to operate well, i.e. it is able to be alive.

If $\Psi(P)$ approaches the boundaries of R_A , the danger of system functional death arises.

It can be shown that in the case that among all p_j time dominates, the **trajectory $\Psi(P)$ remains inside R_A for a limited interval of time only, except the hypothetical case that for eventual system restorations and repair, an unlimited amount of mass, energy and information is at our disposal. For all other cases, one at a certain moment comes to a situation where all the disposable reserves for system parameter corrections and restorations are exhausted and therefore the particular system must fail in its ability to operate well, i.e. must functionally die** (Theorem 2)

This pessimistic statement can be expressed as the theorem of necessary functional death of all closed systems.

Only for an ideal open system and as such only the whole universe can be considered, this is not valid. However, unfortunately all real systems have to be considered from this respect as closed.

This theorem is true for time as an independent variable, because – except for science fiction and some boundary physics consideration, time flows in one direction only and we have at our disposal no tool by which we can realize any influence on the speed (and direction) of this flow.

All other independent variables, of any physical nature, can change their speed and direction of development and, therefore, the above mentioned theorem can not be true if they are considered as dominant for the respective system. This means that in these cases, the trajectory $\Psi(P)$ can remain inside R_A without any principal restriction.

Under system reliability $H(P)$ one can therefore understand the probability that for a certain interval of time (or other independent variable), the trajectory $\Psi(P)$ varies only within R_A (D 1)

Taking into account what was said above, we see that for all closed systems and the vector P of independent variables with a dominant time component,

$H < 1$.

The analysis of the form and shape of $\Psi(P)$ is therefore the basis for any serious considerations of system reliability and safety.

Let us now turn our attention to a characterization and brief description of the most important methods for investigation of regions of acceptability.

These methods can be divided into those which are based on searching for an answer if a certain point X from X is inside or outside R_A i.e. if

$$X \in R_A \quad (15)$$

holds or not, and into those in which some bodies approximating the R_A boundaries are found.

The first group can be classified from various aspects, however, the following two may be considered dominant:

the character of analysis,

the character of R_A expression.

With respect to the first classification, we have to distinguish the

direct and indirect approach

deterministic and the

statistical methods.

With respect to the second classification, we have to consider if the knowledge of R_A is received in the form of a set of data representing its boundary, or if it has the form of information expressing the set of R_A approximating bodies.

This aspect has of course also influence on the necessary storage capacity (in the case that one has to deal with systems for which the operation in multidimensional space is necessary, this aspect can be of extraordinary importance).

4.1.1 Direct approach

Let us now consider a very simple case shown in Fig. 4.4.

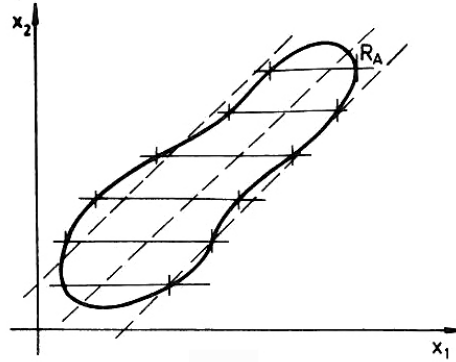


Fig. 4.4 The case of deterministic analysis of R_A by the set of one-dimensional cuts parallel to one axis of the $\{X\}$ space.

One starts the analytic procedure by a systematic choice of points along a certain line and testing if for a particular X the inequality (2.1) holds or not. We store the results, i.e. the values of X and the answers. Then we move the investigated point one step along the chosen line and ask again, if (8) is true or not. If yes, move again in the same direction, if not, store the result and move in the opposite direction and continue, till the answer to the question if (8) holds or not changes. Then we decrease the size of the movement along the chosen line, e.g. to one half and continue, till the acceptable approximation of the point laying on the intersection of the chosen investigation line with the R_A boundary is found. Then we select another investigation line parallel with the previous one, at a certain distance along the next axis of the X space.

So, step by step we receive a set of points lying acceptably near to the boundary of R_A . The investigation can be improved by the use of an additional set of parallel cuts, either along another axis of the X space, or along any preferred direction (e.g. along the normal to the longest found cut).

Suppose now further that we have to deal with a system consisting of ν_k functional blocks, whose properties are represented by partial system functions $F \nu_k$.

The functional properties F of the whole system can be represented as

$$F = \Theta_{\nu=1}^{\nu=\nu_k} F \nu_k, \quad (16)$$

where Θ is some operator dependent on the arrangement of the partial functional blocks in the system. E.g. for a well known simple cascade connection of partial functional blocks without any feedback, often used especially in telecommunication, Θ has the form of product $\Pi_{\nu=1}^{\nu=\nu_k}$.

Having knowledge of the shapes and sizes of R_{A_v} of the partial functional blocks (suppose that they are significantly simpler than the considered system), we now have to ask what are the relations between these R_{A_v} and the R_A of the whole system.

The general answer to this question is not known at the moment, unfortunately.

We do not know either the general transformation between R_{A_v} and R_A , or the respective algebra. The investigation of this is an important challenge in the theory of system reliability.

In simple cases, like the above mentioned cascade connection of partial functional blocks, the investigation of R_A for the resulting system can be easier.

In Fig. 4.5 an example is shown.

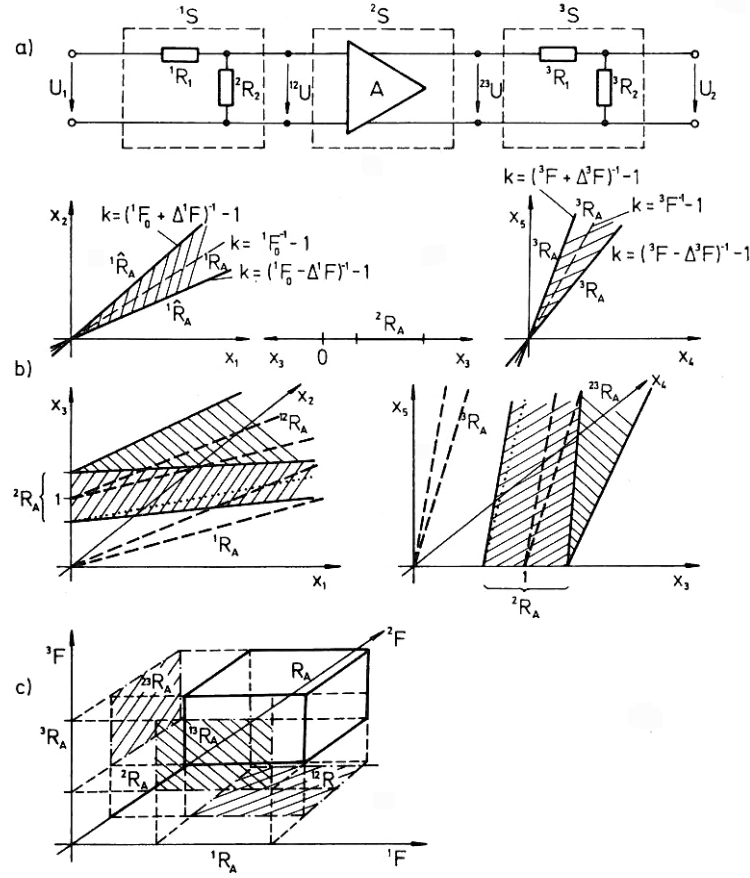


Fig.4.5 A case of a simple system S consisting of cascade connection of three partial functional blocks 1S , 2S and 3S .

Suppose that there is no impeding influence on the interfaces between the functional block 1S and 2S , and also between 2S and 3S , i.e. that both these interfaces operate ideally.

Then

$$F = \prod_{v=1}^3 {}^v F,$$

where $^1F = {}^1R_2({}^1R_1 + {}^1R_2)^{-1}$, $^2F = A$, $^3F = 3R_2({}^3R_1 + {}^3R_2)^{-1}$.

Let us assume, that the values of the functions ${}^v F$ of partial functional blocks $1S$, $2S$ and $3S$ can change about $\pm \Delta {}^v F$.

Then the regions of acceptability 1R_A and 2R_A have the form of cuts between straight lines in the planes $\{{}^1R_1, {}^1R_2\}$ and $\{{}^3R_1, {}^3R_2\}$, originating under the angle corresponding to values ${}^1F_0 \pm \Delta {}^1F$ and $3F_0 \pm \Delta {}^3F$ and the region $2FA$ is the line of the length $2\Delta {}^2F$ between the points $2F_0 \pm \Delta {}^2F$ on the axis A . The resulting R_A is a body in a 5 dimensional space

$$\{X\}_5 = \{x_1, x_2, x_3, x_4, x_5\},$$

where

$$x_1 = {}^1R_1, x_2 = {}^1R_2, x_3 = A, x_4 = {}^3R_1, x_5 = {}^3R_2,$$

when the projections of this body in the planes

$\{x_1, x_2\}$, $\{x_3\}$, $\{x_4, x_5\}$ are known, eventually also the intersection body $^{12}R_A$ or $^{23}R_A$, corresponding to a cascade connection of the partial functional blocks 1S and 2S or 2S and 3S is known (see Fig. 4.5b).

The graphical representation of the whole region R_A in the 5-dimensional space $\{X\}_5$ is out of our possibilities.

However, we can represent this region R_A in a three dimensional space $\{^V F\}_3 = \{1F, 2F, 3F\}$, where the values of system functions $^V F$ of partial functional blocks are drawn on the axis.

So we receive the body shown in Fig. 4.5c. Because here $F = {}^1F \cdot {}^2F \cdot {}^3F$, the whole of this hyper-rectangle is the requested R_A .

If one analyses the sizes and shapes of R_A for systems consisting of functional blocks for which one knows the partial R_{A_v} , one has to solve the problem of determining the whole body from the known set of its projections or cuts. Some methods from stereo-metric can be applied to solving this problem.

Suppose now, that we deal with partial functional blocks, whose system functions $^V F$ are of scalar nature. The R_A of this system can be therefore analyzed in the less dimensional space $\{^V F\}_{\nu_k}$, taking into account the relation (16).

If this is of the above mentioned product form, the respective R_A has the form of a hyper-rectangle, whose edges are limited by the values of allowed deviations $\Delta^V F$ of the functions $^V F$ from their nominal values $^V F_0$.

Inside this body of R_A , the surfaces are $F = \text{const}$ which in this case have the form of ν_k dimensional hyperboloids, the example of which is for the $\nu_k = 2$ shown in Fig. 4.6.

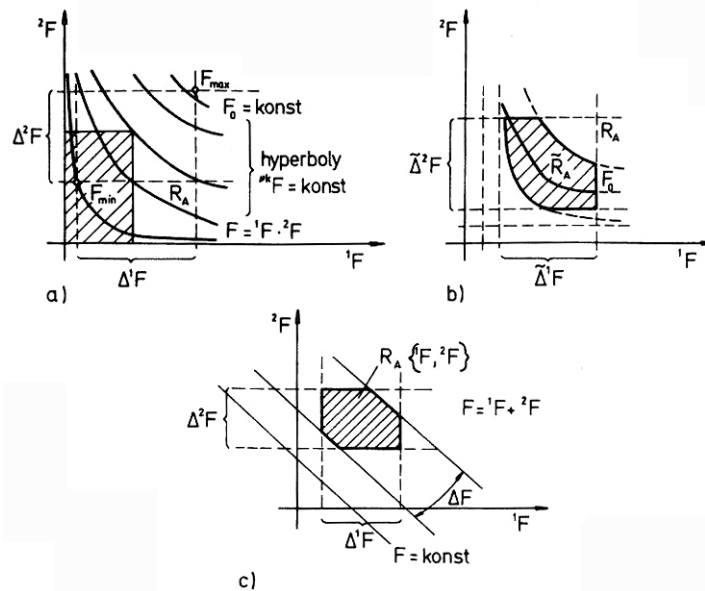


Fig. 4.6 The region of acceptability R_A and the lines $F = \text{const}$ in the plane $\{^1F, ^2F\}$.

In Fig. 4.6a a certain line $F = \text{const}$ corresponds to $F = F_0$ and the intersections of the sets of these hyperboloids with the body of R_A determine the useful range of the values F . If the size of allowable deviations of the functions $^V F$ is diminished from the original values $\Delta^V F$ to $\tilde{\Delta}^V F$, these projects into the region of acceptability by excluding certain of its parts, namely those which are closest and most distant to the origin (see the Fig. 4.6b). It is evident, that under these circumstances, one can replace the original considerably laborious analysis of R_A in an N dimensional space $\{x_i\}$ by a much simple analysis of partial regions of acceptability in only an $^V N$ dimensional spaces and in one resulting region of acceptability in an $\Delta^V F$ dimensional space $\{^V F\}_{\nu_k}$.

For many applications, namely in electronics, informatics and telematics, where the product form of eq. (16) is valid, the respective regions of acceptability for partial functional blocks have the form limited by two hyperboloids of ν_k dimension and by planes parallel to the axes $^V F$.

Further, in practice often appearing form of the expression (16) is the summary form, corresponding to the parallel ordering of partial functional blocks (of course, only under some specific physical conditions). Here we have

$$F = \sum_{v=1}^{V=V_k} {}^V F \quad (17)$$

For these cases, the partial regions of acceptability ${}^V R_A$ can be represented by cuts of the whole N dimensional space $\{x_i\}_N$ for ${}^V F_i = 0$. If one knows the shapes and sizes of ${}^V R_A$, one can again by the use of proper (especially of the geometrical) methods find the resulting R_A . If only the scalar values of ${}^V F$ are considered, also here the possibility of replacement of a considerably complicated investigation of $R_A \{x_i\}$ by a simpler investigation of $R_A \{{}^V F\}_k$ exists. In Fig. 4.6c function values deviations of region $R_A \{{}^V F\}_k=2$ are shown for $F = 1F.2F$ and acceptable $\Delta 1F$, $\Delta 2F$ and ΔF .

Of course, when dealing with a system where the expression (16) has other than the mentioned simple form, the procedure of $R_A \{{}^V F\}$ can be complicated.

Another set of problems appears if the shape of R_A is in some parts of its boundary concave (see examples shown in Fig.4.7)

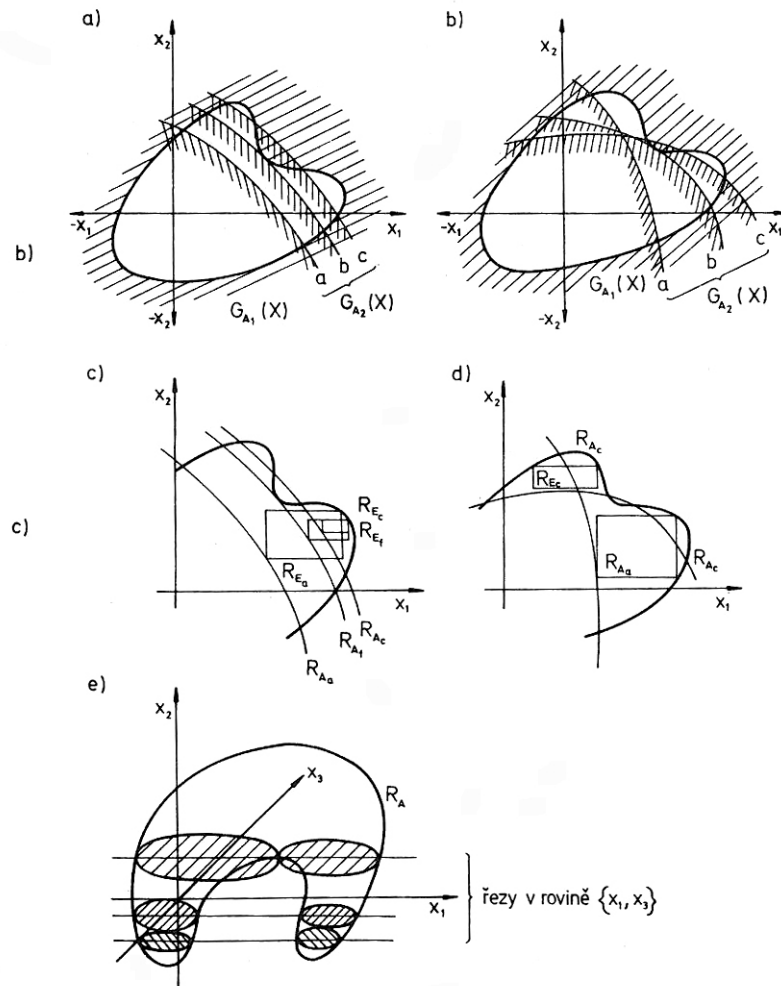


Fig. 4.7 To the problems of R_A with concave, resp. separate parts.

In general, the non-cascade structures can have serious advantages compared with a simple cascade arrangement of partial functional blocks, namely that the sensitivity of the total system function F to changes of partial functional system functions ${}^V F$ can be much lower.

This can cause that the shape of the body F above the space $\{^V F\} \nu_k$ is - at least inside $R_A\{^V F\}$ - much smoother and that, therefore, there are much better preconditions for more accurate determination of the boundaries of R_A , especially when approximate numerical methods are used.

The geometrical properties are very important for the analysis of R_A . We have already discussed the influence of dimensionality and of the number N of considered parameters x_i . However, we also must take into account if the respective regions of acceptability are simple or if they have more separate parts. Some simple examples are shown in Fig. 4.7e and 4.8 and Fig. 4.9.

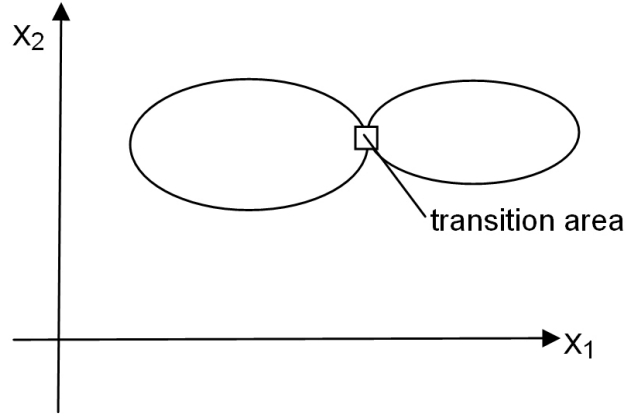


Fig. 4.8: Example of simple consistent R_A

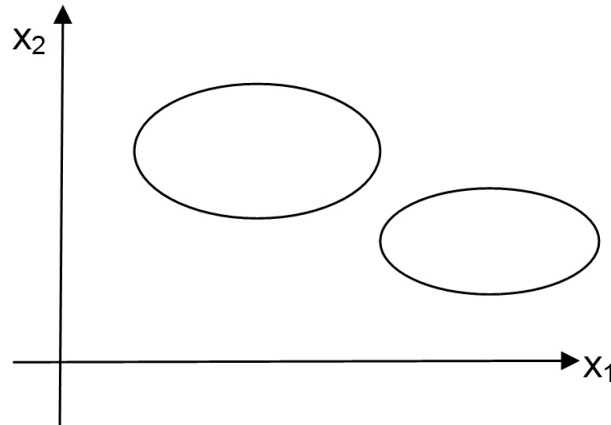


Fig. 4.9 Example of R_A with two separate parts

Unfortunately, from the starting data, i.e. from the expression of the system function $F(X)$ and from the region of its allowable deviances ΔF one cannot usually determine how much the R_A is complicated. At present there is no direct method for this analysis at our disposal and therefore one has to modify each applied analytical procedure with respect to the nature of the considered problem.

Suppose, that there is known a set of limited conditions $G_A(X) \leq 0$, determining in the space $\{X\}^N$ the boundaries $\tilde{R}_A$ of the region of acceptability R_A .

Then the R_A can be defined as

$$R_A = \overset{\Delta}{\{X | G_A\}} = 0 \quad (18)$$

One can show, that if all the conditions $G_A \mu(X)$ from the set $G_A(X) = \{G_1(X), G_2(X), \dots, G_A \mu(X), \dots, G_{AM}(X)\}$ are convex, than the R_A which they all together determine is simple, without separate parts. However, if at least one of these conditions is concave, the respective R_A may but need not have separate parts.

Naturally, there exist cases where the existence of some separate part of R_A is detected only after the considerably laborious numerical investigation of the respective boundaries $\tilde{R}_A$. This situation can of course have serious influence on all further procedures concerning the optimization of the particular system design.

Beside this, a situation can also appear where one finds that in a certain cut through R_A some separate parts appear, but one is not able to determine if they represent the real existing separate parts or if they are caused just by an improper intersection of the respective cut with the considered R_A (see Fig.4.8e e.g.).

Almost the information on convexity or at least on one-dimensional convexity has the same value as the information concerning the existence of separate parts of R_A . Suppose that for a certain $X = X_m$ the corresponding system function F has its minimal value $F = F_m$. Then for any $X \neq X_m = X_m + \Delta F$, $\Delta F > 0$ the corresponding $F > F_m$ and we can formulate the condition of convexity as:

the region R in the space $\{X\}$ is convex if

$$F[(X_A) + \lambda (X_B - X_A)] = F(X_A) + \lambda [F(X_B) - F(X_A)] \quad (19)$$

for any $0 \leq \lambda \leq 1$ and for any pair of points X_A, X_B inside R .

If $R \rightarrow R_A$, the condition of complexity holds also for R_A , i.e. if $X_m \in R_A$ so that the corresponding $F_m = \text{Min } F$, then for convex R_A for all $X \neq X_m$ $X \in R_A$ is $F > F_m$.

Suppose that some R_E has the shape of a polyhedron whose all vertexes lie inside the R_A . Then $R_E \in R_A$ in the condition (19) holds.

There exist the cases where the condition (19) is valid only in some directions, while in others it is not. Then one speaks about R_A with one or more dimensional non-convexity (concavity).

A simple example is shown in Fig. 4.10.

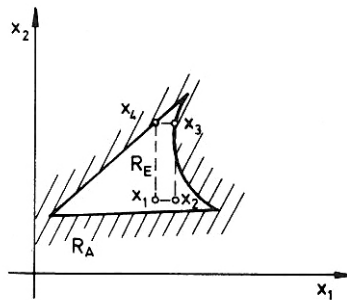


Fig. 4.10 Simple example of one dimensional concave region for $N=2$

Here one can see that in the direction of the axis X_2 the R_E cannot approximate R_A .

Some special situations of one-dimensional convexity will be discussed later on.

The multi-variability of the space $\{X\}$ and also of the body of the functions F above it causes that one cannot point out any universal or most suitable method for the analysis of regions of acceptability, though in literature on the theory of system reliability and system tolerances many various approaches to solving this important task are described.

As we have already mentioned, none of them is universal, some have advantages in certain cases, the others somewhere else. In analyzing a real case, one therefore often has to use some suitable combination of several such methods. Besides several empirical recommendations for the choice of the combination, no exact rule for preferring this or that method is known at the moment. The finding of the proper combination of suitable methods for R_A analysis and recommendation of the sequence of their application requires a high level of experience and belongs to the art of reliability analysis and optimization.

Later on we will briefly characterize also some of the most important partial approaches to the analysis.

However, before that we shall set out some important consequences.

The boundaries $\tilde{R}_A$ of the regions of acceptability R_A , defined above, depend first of all on the character of space X only and not on the properties of the body of system functions F . Therefore one can expect that for finding $\tilde{R}_A$ one does need further information.

However, this is true only if one analyses $\tilde{R}_A$ through some direct methods, e.g. those of analytic nature. Unfortunately, the applicability of these approaches is limited to simple or special cases only.

When dealing with indirect methods which one has to use in many other cases, one needs to have at his disposal also certain information concerning the density of probability $\Phi(X)$ of the appearance of X values in the R_E or at least of its acceptable approximation. In some cases, also the knowledge of the internal structure of R_A is required, e.g. in the form of the set of boundaries $\tilde{R}_{Aj}$ holding for different values

$$\Delta_j F \neq \Delta F.$$

A special part of the problems of R_A investigation is the presentation (and also the storing) of the results of R_A analysis. If one deals with low or modest degrees N of system dimensionality ($N < 4$ or 5), one can represent the significant cuts or projections of R_A in a graphical form. However, for N above this, the graphical form is of small or almost no use. E.g. just for $N = 4$ the recording of R_A analysis requires the representation of a 4 dimensional body into 6 projections, for $N = 5$ these projections are 10, for $N = 6$ one needs 15 projections, etc. Moreover, only the knowledge of all such projections is usually not sufficient for satisfactory information about the respective R_A . Therefore we need beside this to know also some cuts through the particular R_A , usually by planes parallel with some significant plane in the X_N space.

Therefore, it is recommended to restrict oneself, when analyzing R_A , only to projections and cuts which one can directly use for the considered optimization of the particular system properties.

A considerably good results can be achieved in the cases of higher values of N if one uses a suitable approximation of $\tilde{R}_A$ constructed by filling it out by the set of a deterministic regular body or by a set of approximating bodies. Then the number of parameters necessary for an R_A or $\tilde{R}_A$ specification can be much lower.

One example is shown in Fig. 4.11, of course here drawn for $N = 2$ only. The approximation of $\tilde{R}_A$ is made by the set of circles (in an N dimensional case the hyperspheres). The approximating bodies are evidently the best choice with regard to the requirements on the storage capacity – for storing the satisfactory information of one hypersphere one needs to store only $N+1$ numbers: N for the location of the hypersphere's center and 1 for its radius. Of course, the total necessary memory capacity for the approximated R_A storing depends significantly on the size and sequence of the approximating hyperspheres. In general, it can be recommended to start with the maximally large hypersphere which can be inserted inside the particular R_A . However, its size varies with the choice of the starting point.

In Fig. 4.11, the point x_1 was chosen as the starting point. Starting from here, the radius ρ_1 as the largest possible spherical approximation S_1 of R_A was found, with a contact point $1x$. As a further step the straight-line v_1 connecting points $1x$ and x_1 was prolonged till its intersection with $\tilde{R}_A$ was found in the point $2x$. Here the normal to the $\tilde{R}_A$ surface v_2 is constructed and the point x_2 representing the center of the largest inserted second spherical approximation S_2 of the radius ρ_2 is determined. The line v_2 as the prolongation of the straight-line between the points $2x$ and x_2 is constructed further on and its intersection with $\tilde{R}_A$ is found again. So, step by step one can fill out $\tilde{R}_A$ with approximating hyper-spheres.

However, in practical realization of the procedure some questions remain, e.g.,:

What is the best place for the starting point x_1 ?

How to construct the normal to the $\tilde{R}_A$ surface in the contact points k_x , where k means the respective approximation step?

Whether the selection of the normal direction of the straight-line v_k is the best strategy?

How to ensure that the approximating hyper-spheres do not overlap?

How to modify this procedure if some concave part of $\tilde{R}_A$ appears?

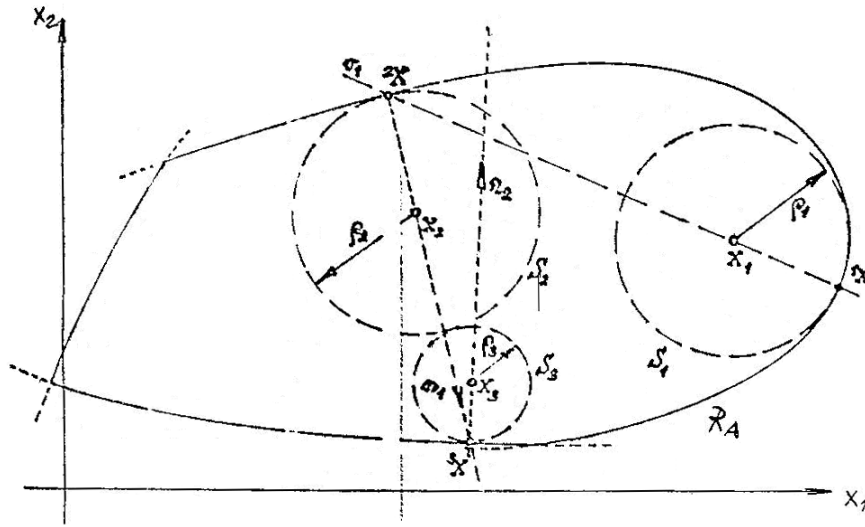


Fig.4.11 The approximation of R_A by the set of hyper-spheres

The answers to these questions are not easy and depend also on the character of the searched $\tilde{R}_A$. Nevertheless, for representing such a set of approximating hyper-spheres one needs to know the table of their centers coordinates and the table of their radii (see e.g. [1], [5]).

The existence of the above mentioned open questions concerning the hyper-spherical approximation of $\tilde{R}_A$ has lead to development of another kind of similar approximation procedure, presented in the late seventies by Director and Hachtel (see [20, 21]).

Their method is known in the literature as "simplicial approximation".

Its principle is shown in Fig. 4.12 for $N=3$.

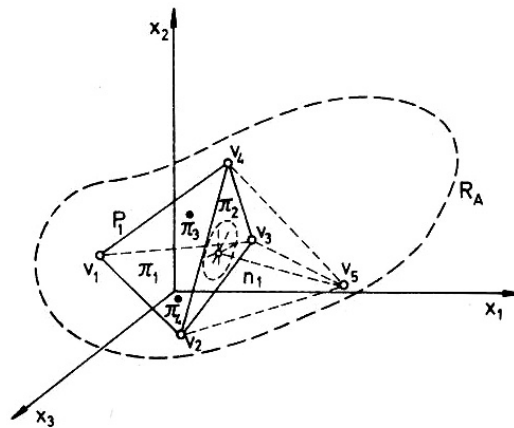


Fig.4.12 The principal of simplicial approximation of $\tilde{R}_A$

Here the simplest, i.e. the linear approximation is used.

Suppose again that $\tilde{R}_A$ has no concave parts. Then it can be approximated from inside by the N -dimensional polyhedron P_k with vertexes $v_1, v_2, \dots, v_\lambda$, where $\lambda = N+1, N+2, \dots, k$, lying enough close to the $\tilde{R}_A$ from inside. The polyhedron can be characterized as $P_k = \{X \leq n_i X \leq b_i\}$ for $i=1, 2, \dots, N$, where n_i are normals to the polyhedron sides π_j ($N-1$ dimensional hyper-planes), defined as

$$\pi_j = \{X \in R_A \mid n_i X = b_i\}.$$

These normals have the direction out from the polyhedron to $\tilde{R}_A$, and b_i represents the distance of the hyper-plane from the origin and N_k is the total number of sides (hyper-planes) of the polyhedron inscribed in the k -th iteration in the N -dimensional region R_A . The first polyhedron is usually determined as a convex body, determined by the set of $N+1$ vertices, lying on $\tilde{R}_A$ or in its close vicinity.

This set is found in the course of a subsequent investigation if the points X along respective axis of the space $\{X\}$ or along lines parallel to them satisfy the condition $X \in R_A$ or not. In a further step one finds the largest hyper-plane π_j , in the center of its gravity one constructs the respective normal and along it one finds the point, satisfactorily close to $\tilde{R}_A$. This represents the vertex of the next approximation polyhedron. Fig. 4.12 shows the procedure for $N=3$. In the original presentation [20, 21] was used as the figure of merit of the site of a particular hyper-plane, the radius of the largest hyper-sphere which was possible to inscribe in individual hyper-planes π_j .

Various strategies can be used to find further vertices of the approximation polyhedron in the course of its step by step enlargement.

A few years after Director and Hachtel, Hachtel, Sangiovanni-Vincentelli and Visvanathan showed in [22] some possible approximation strategies ensuring the convergence of the whole procedure in the cases of a convex R_A . Some other strategies have problems when applied to a convex R_A . The situation is shown for $N=2$ in Fig 4.13.

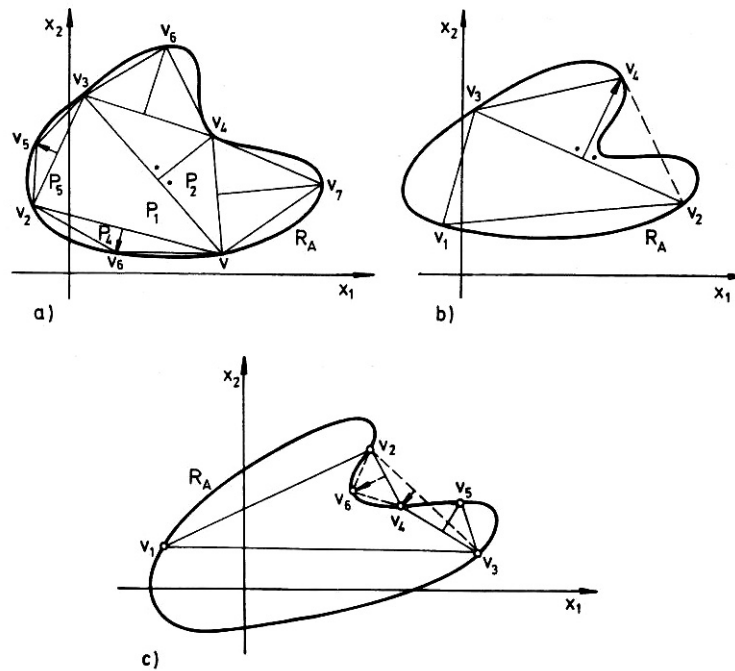


Fig. 4.13 The principles of simplicial approximation to the case of R_A with concave parts.

The situation is presented in Fig. 4.13a. Suppose that one constructs the approximating polyhedron P_k even in the case when one cannot ensure that all parts of P_k are inside R_A . One can proceed as follows:

For each side π_j of P_k the center of gravity is determined. In the respective points P_j the test is made to find out if $P_j \in R_A$. If yes, one proceeds as mentioned above. If not, one constructs the normal in P_j in the opposite direction, i.e. in the direction inside the R_A .

Along it, one finds the point v_{j+1} in the direction inside R_A . It is possible to show that the procedure converges and that it leads to polyhedral approximation, however, with some parts inside the R_A and other parts outside.

There are situations in which such an approximation is acceptable.

If this is not the case, one can – if $F(X)$ is inside $\tilde{R}_A$ continuous – slightly diminish the value of the allowable system function deviation from the original ΔF to $\Delta_d F$ which corresponds to a smaller region of acceptability R_{Ad} . Then one can expect that by proper choice of $\Delta_d F$ the approximating P_k will be inside R_A .

As an extension of the idea of “simplicial approximation”, the approach based on the use of higher degree approximation can be mentioned:

Let us focus on many technical systems where one cannot expect that the searched R_A will be in all its parts convex. This can be considered here, therefore, as an intersection of certain sub-regions which are convex or complementary convex (i.e. their complements are convex). The most general cases are those that are quasi-convex or quasi-concave in the sense of the following definition:

Function $F(X)$ is in a certain part $\{X\}_N$ of the space $\{X\}$ quasi-convex, if for an arbitrary $X_1 \in R_A$, resp. $X_2 \in R_A$

$$F[\Theta X_1 + (1 - \Theta) X_2] \leq \text{Max} [F(X_1), F(X_2)], \quad (20)$$

where $0 \leq \Theta \leq 1$.

Function $F(X)$ is in a certain part $\{X\}_N$ of the space $\{X\}$ quasi-concave, if the function $-F(X)$ is in this part quasi-convex.

If the function $F(X)$ is differentiable, the inequality 20) can be replaced by implication

$$F(X_2) \leq F(X_1) \Rightarrow \nabla F(X_1) T(X_2 - X_1) = 0 \quad (21)$$

Director and Hachtel have presented in [20] a method in which the quasi/concave part of R_A is approximated again linearly by hyper-planes, however, in this case projected from inside the R_A tangentially to its surface (see Fig.4.15).

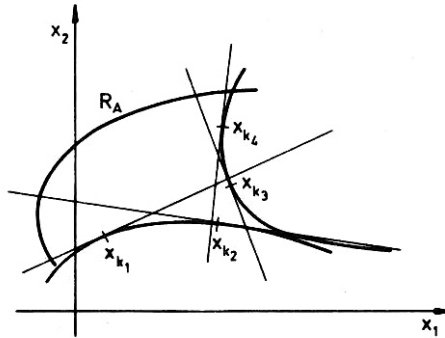


Fig.4.14 Linear approximation of quasi-concave part of R_A by hyper-planes according to Director and Vidigal.

Such approach can be extended to use of nonlinear curves or planes, see Fig. 4.15. Of course, its natural limitation is in processing complexity.

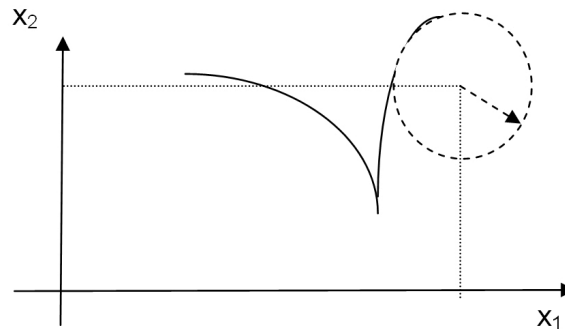


Fig. 4.15 Approximation of quasi-concave parts of R_A by nonlinear approximants (dotted lines).

4.1.2 Indirect methods of R_A analysis

From the definition of the region of acceptability one can see that the problem of its analysis is principally of a deterministic nature and the statistic $\Phi(X)$ of the X vector values appearance in the RE region does not have any influence on its result. Therefore, if the analytical expression of $F(X, P)$ is known, the analysis of R_A can be done directly, just by finding the geometrical place of points, for which

$$F(X, P) = \text{const} \quad (22)$$

However, there remains the question if the task (22) is solvable, and if yes, how to solve it.

Let us now deal with the possibilities of finding the analytical expressions for the boundaries $\tilde{R}_A$.

If the analytical expressions for $F(X)$ are known and if one neglects the influence of independent variables P and if in the K -dimensional space $\{F_k\}_K$ the regions of allowable deviations ΔF of the system functions are known, the task of determination of $R_A\{X_N\}$ is a mapping of the region ΔF into the space $\{X_N\}$. In the simple cases when F is of the scalar nature we have

$$\left. \begin{aligned} F(X) \pm F_0(X) &= \Delta F, \\ F(X) &= \Delta F \mp F_0(X) = \text{const}, \end{aligned} \right\} \quad (23)$$

which is a modification of eq. (22).

The possibilities of analytical solution of the previous two equations depend on the complexity of the set of system functions $F(X)$. Generally, a set $\{F_k\}_K$ of K algebraic differential equations has to be solved, in which

$$F_k(u, u, X, t) = \text{const} \quad (24)$$

and u is the vector of signals acting in the nodes and branches of the considered system, $\dot{u}$ are their derivatives with respect of time t and X is the vector of system parameters.

It is evident that the analytical solution of eq. (24) is possible in a limited number of cases only.

An interesting case are linear electric systems whose system functions have the form of rational functions (fraction of two polynomials $A(p)$ and $B(p)$ with real coefficients) in the complex frequency $p = \sigma + j\omega$. Macura in [23] has used the properties of such system functions for development of a simple direct procedure for analysis of R_A of these systems.

Another extension of the approach was presented by Bandler and Liu already in [24]. They showed that if $F(x_i, p) = A(x_i)/B(x_i)$ where $A(x_i)$ and $B(x_i)$ are quadratic trinomials in x_i ,

the expression for sensitivity to large changes of x_i can be expressed as

$$\frac{\Delta F_k}{\Delta x_i} = \frac{F(x_{iU}) - F(x_{iL})}{x_{iU} - x_{iL}} = \frac{\Delta x_i F'_k(x_{iL}) \frac{A(x_{iL})}{A(x_{iU})} - \Delta x_i^2 \frac{F'_k(x_{iL}) - F'_k(x_{iU})}{A(x_{iU})}}{\Delta x_i},$$

where x_{iL} and x_{iU} are the lower and upper limits of the parameter x_i and $F'_k = \partial F_k / \partial x_i$.

Bandler and Liu also showed that:

the maximum, resp. minimum of the function $F_k(x_i)$ in the interval $x_{iL} \leq x_i \leq x_{iU}$ is on the edges of this interval, if at least one of the following conditions is valid:

- a) $F'_k(x_{iL}) \leq 0$ and $F'_k(x_{iU}) \leq 0$,
- b) $F'_k(x_{iL}) \geq 0$, $F'_k(x_{iU}) \geq 0$ and $F_k(x_{iL}) < F_k(x_{iU})$,
- c) $F'_k(x_{iL}) < 0$, $F'_k(x_{iU}) < 0$ and $F_k(x_{iL}) > F_k(x_{iU})$.

Then the considered interval has a convex character.

This can be useful information for investigation of regions of acceptability.

Let us now turn our attention to other kinds of systems which have interesting properties for investigation of R_A .

These are the systems with multi-valuability and /or with hysteresis and these systems appear quite often among real systems, either of the artificial or of the natural character.

As concerns the technical systems, these are namely the logical electronic functional blocks whose significance for practice is out of any discussion.

As a very simple example let us consider the bi-stable flip-flop block, shown schematically in Fig. 4.16.

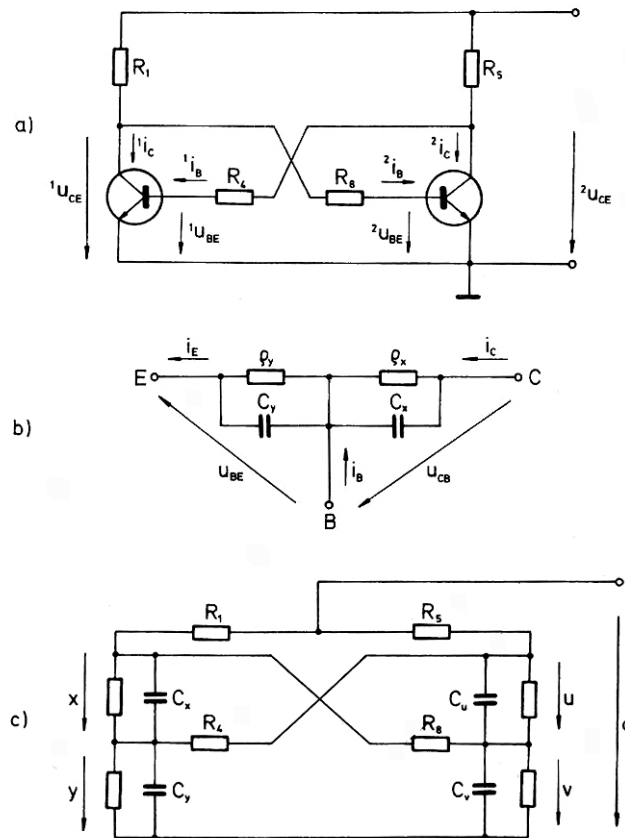


Fig. 4.16 Simple flip-flop functional block

The value of signal $^2U_{CE}$ on its output gate varies from the logical zero to which the value of system function F_L corresponds to the logical one, to which the value F_U corresponds. Between these two limit values the system function F is not defined – this corresponds to the region of uncertainty.

The procedure of switching from F_L to F_U depends apart from the level of input signal $^1U_{CE}$ on input gate also on some of system parameters x_i . Suppose that one of them can influence the ability of the considered block to switch on external stimulus 1U from the stage F_L to the stage F_U and back.

In Fig. 4.17 are shown the idealized forms of this dependence. Here we see that the transition from the lower level to the upper one and back depends on the sense of the change of the parameter x_k . The way of the realized transition in one and in other direction is not the same. This phenomenon is known as “hysteresis”. This is very often present in many real systems, either of electronic, magnetic, mechanic or other nature. Actually, it is very hard to realize any system absolute without hysteresis because this phenomenon has a close relation to internal dissipation of energy and friction.

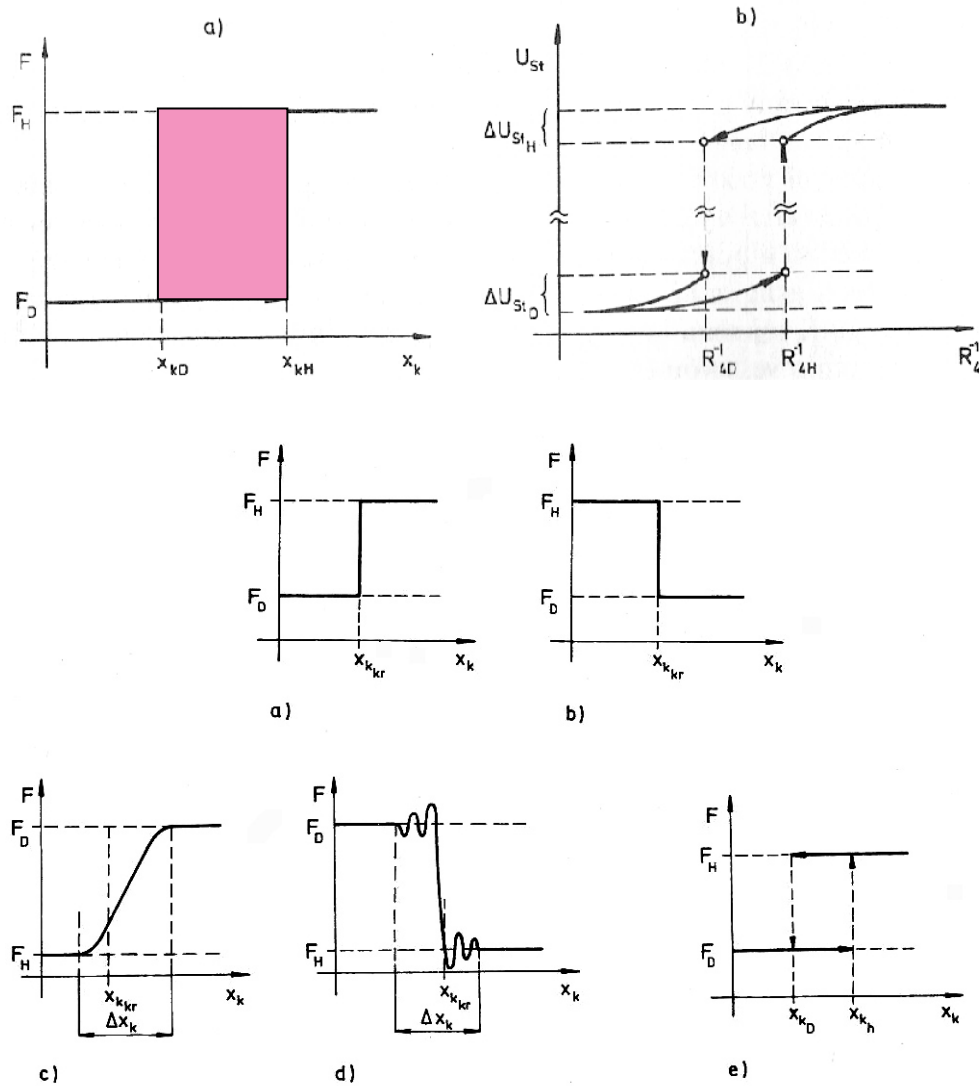


Fig. 4.17 System functions for a simple flip-flop functional block:
a), b) ideal forms of system function of a flip-flop functional block
c) smooth transition of the flip-flop functional block system function from one stage to another one
d) transition of the flip-flop functional block system function with oscillations
e) transition of the flip-flop functional block system function with hysteresis (see also Fig. 3. 15).

The size of the pink shaded area in Fig. 4.17a is principally proportional to the strength of hysteresis, corresponding to the energy which must be spent to change the stage of the system.

In reality, the transition is never as sharp as shown in Fig. 4.17a, but it is more like that shown in Fig. 4.17b. This corresponds to a situation where the resistors R_1 , R_5 and R_8 in Fig. 4.16a remain constant and the R_4 varies.

The dependence of a system function on one system parameter is very similar to the second elementary catastrophe called “cusp” of the seven elementary catastrophes, found by French mathematician R. Thom (see [25] [26] e.g.).

These seven elementary catastrophes can be expressed as:

$F(v_j, x_i):$	
$1/3 v^3 + x_1 v$	fold
$1/4 v^4 + 1/2 v^2 x_1 + v x_2$	cusp
$1/5 v^5 + 1/3 v^3 x_1 + 1/2 v^2 x_2 + v x_3$	swallow tail
$1/6 v^6 + 1/4 v^4 x_1 + 1/3 v^3 x_2 + 1/2 v^2 x_3 + v x_4$	butterfly
$v_1^3 - 3v_1 v_2^2 + x_1(v_1^2 + v_2^2) + v_1 x_2 + v_2 x_3$	elliptic umbilic
$v_1^3 + v_2^3 + v_1 v_2 x_1 + v_1 x_2 + v_2 x_3$	hyperbolic umbilic
$v_1^2 v_2 + v_2^4 + v_1^2 x_1 + v_2^2 x_2 + v_1 x_3 + v_2 x_4$	parabolic umbilic

Here $v_1, \dots, v_M$ are the system variables, which are functions of time $P = t$, and $x_1, \dots, x_N$ are the system parameters, which can also depend on time.

The second elementary catastrophe can be sketched as shown in Fig.4.18.

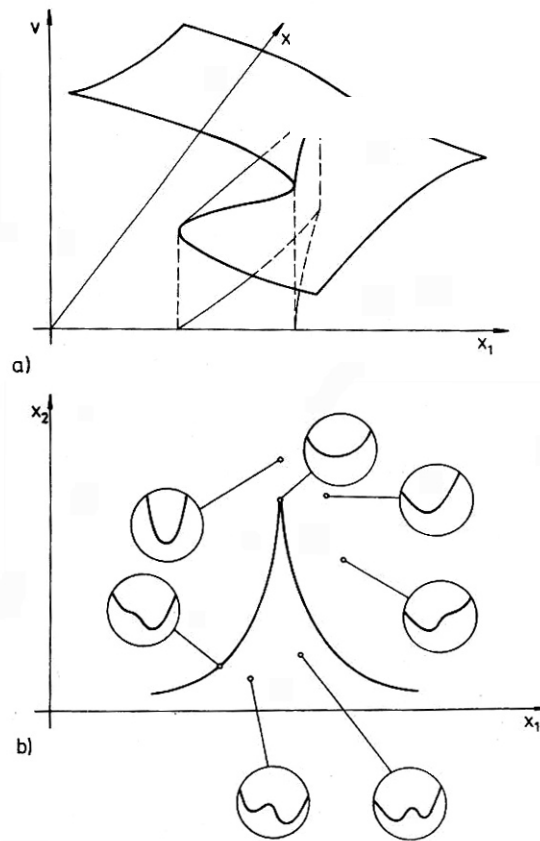


Fig. 4.18 Sketch of Thom second elementary catastrophe.

The various two dimensional curves shown here result from cuts, presented in Fig. 4.19.

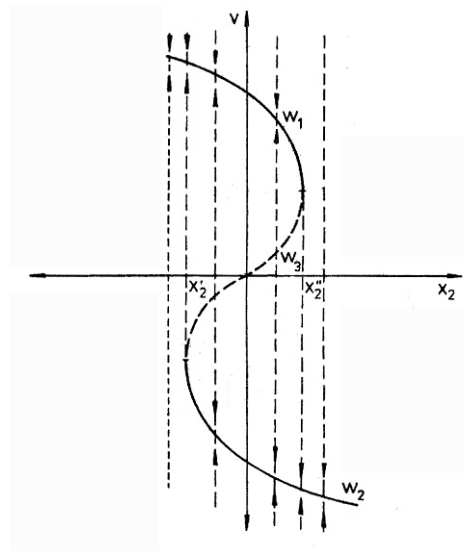


Fig. 4.19 Various cuts in the second elementary catastrophe.

This type of the second elementary catastrophe can be used also as a model for the behavior of various mechanical constructions, some examples of which are shown in Fig.4.20.

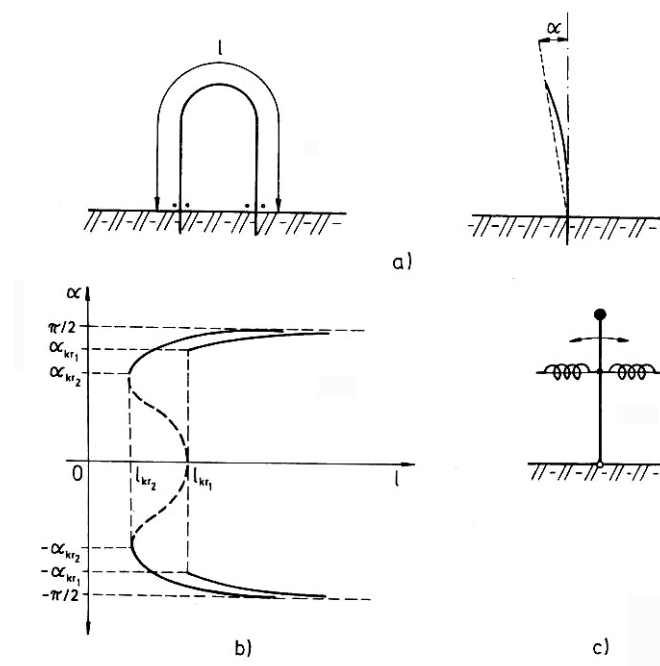


Fig. 4.20 Examples of simple mechanical devices, the behavior of which can be modeled by the second elementary catastrophe.

This type of catastrophe can serve also for approximation of the region of acceptability of the considered simple logic functional block. For this catastrophe the behavior of the respective system depends on two parameters in general.

Therefore we can proceed in two following ways:

either we select from the set of relevant system parameters the corresponding the top-less in between which similar relations to the “cusp” model hold,

or we search for two auxiliary system functions whose properties can be approximated by the catastrophe “cusp”.

An example of this procedure was presented already in [1]. Through this analogy one can almost in direct form analyze the shape and size of regions of acceptability of many logic functional blocks. An example of a system function for the simple flip-flop logic block is shown in Fig. 4.16.

Here the effect of hysteresis has to be taken into account, see Fig. 4.21.

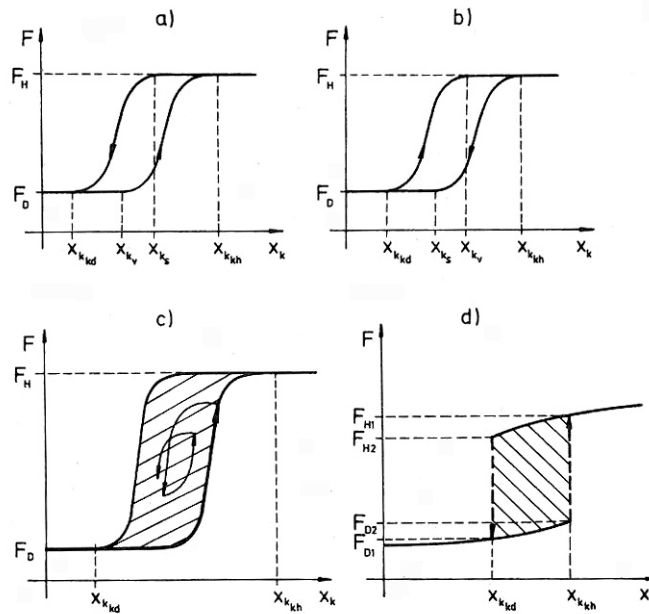


Fig. 4.21 The phenomenon of hysteresis. As in Fig. 4.17, the dashed area corresponds to the energy spent for one cycle.

There are many systems dealing with whose system functions one has to expect hysteresis behavior.

To these belong also advanced models of system interfaces, especially of those which more or less accurately approximate the behavior of biologic synapses, operating among neurons (or other living cells).

An example of models based on the technology of re-programmable neural switched is introduced in [27].

Fig.4.22 shows the schematic cut through a microelectronic semiconductor element suitable for integration in solid state functional blocks. In Fig.4.23 are drawn the corresponding positive and negative resistance characteristics.

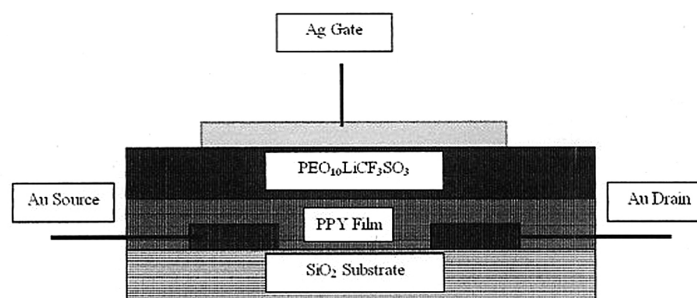
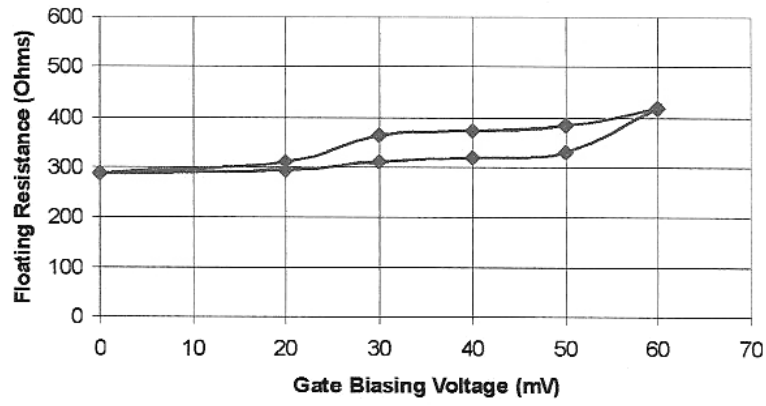
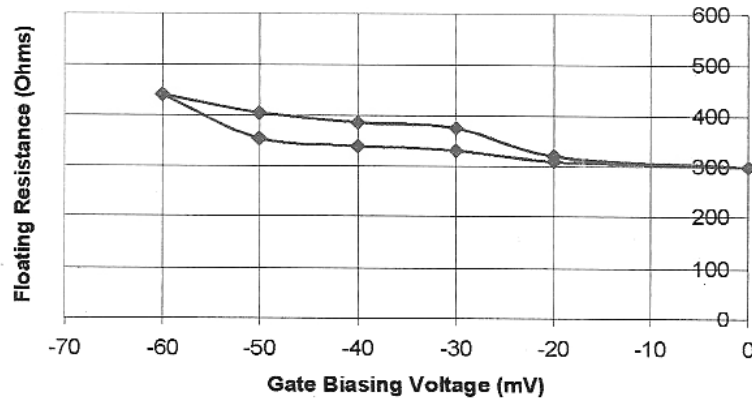


Fig. 4.22 Reprogrammable neural switch (RNS)



a)



b)

Fig. 4.23 Positive (a) and negative (b) programming cycle for RNS microelectronic element

The regions of acceptability for the logic functional block shown in Fig. 4.16 are shown in the two dimensional space $X = \{R_4, R_8\}$, see Fig. 4.24.

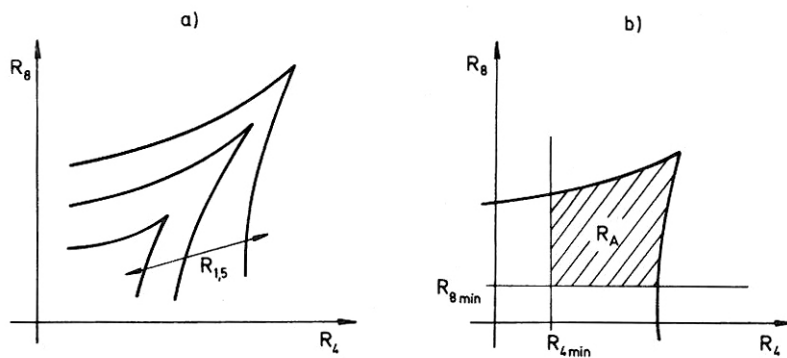


Fig. 4.24 Region of acceptability for a simple logic functional block

4.1.3 Stochastic approaches to R_A investigation

Besides the deterministic methods, some of which were mentioned in paragraphs 4.1.1 and 4.1.2, also stochastic approaches are often used.

The simplest principle of them consists of a random generation of location of the vectors X in the region of possibility R_P and testing, if for each location the condition (8) resp. (12) holds. This principle is sometimes called also the Monte Carlo method.

However, in order to bring real advantages, this simple principle has to respect several important aspects.

The first of them concerns the choice of the density of probability Ψ by which the individual vectors x_i are distributed in R_P . Though in general the use of any Ψ must lead to the same result, the efficiency of the investigation procedure differs significantly upon the choice of Ψ .

Evidently, if the neighbor samples are generated too close one to the other, the probability will be high that the answer whether a particular point x is inside or outside R_A will be the same. In such a case one of the investigations was not necessary. Therefore it is best to choose a probability density Ψ whose maxima are near the boundaries of the searched R_A , see the Fig.4.25.

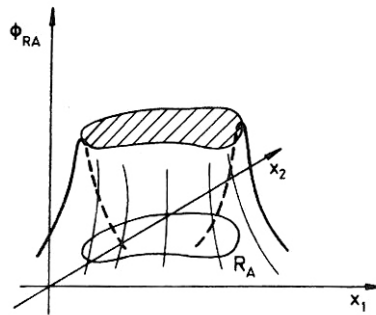


Fig.4.25 Optimal choice of the density of probability Ψ

Of course, this can seem quite a useless idea, because the boundary of R_A is precisely what we do not know. Nevertheless, some improvement can be achieved by a suitable combination of the subsequent combination of several different methods.

Suppose, for example, that we start the search for R_A by finding some point X_0 somewhere inside R_A . The next step can assume that:

- this point is not far from the hitherto not known R_A and that
- the shape of R_A does not differ too much from hyper-sphere.

If these two assumptions are at least a little bit realistic, we can continue using a modification of the well known method of radial sprouting according to Tahim and Spence (see [27]), which principle is demonstrated for $N=2$ in Fig. 4.26.

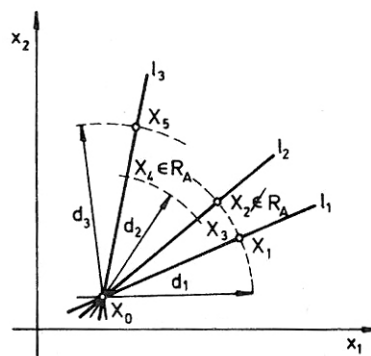


Fig. 4.26 The method of “radial sprouting”

Let from X_0 a line l_1 be radiated in a randomly chosen direction by a step by step testing procedure along this line, the point X_1 , satisfactorily close to R_A boundaries on this line, is found in the distance d_1 from X_0 . As the next operation, the other line l_2 is radiated from X_0 , again in a randomly chosen direction. In accordance with the mentioned assumptions now it is supposed that the point X_2 on l_2 lying acceptably near the boundaries of R_A will be also at the distance d_1 from X_0 . If the respective test gives the answer that this is not true, by

another step by step testing procedure the corrected point X_3 is found. It is highly probable that for its finding a smaller amount of calculations will be necessary than for finding X_1 on l_1 .

The procedure is then repeated by a random radiation of lines l_i till satisfactory information on the R_A shape is achieved. Dealing with this approach, one has to remember that the applicability and efficiency of this method of “radial sprouting” depends significantly not only on the validity of both of the above mentioned assumptions, but also on the chosen kind of the density of probability ψ of the lines l_i radiation procedure.

If necessary, this method can be improved at first by an adaptive modification of ψ and then also by an adaptive moving of the radiation center location.

What is important in all the stochastic approaches when applied to cases of higher dimensionality is the need to minimize the influence of eventual correlations among the partial probabilities ψ_i by which the lines l are radiated in directions of other system parameters. This can cause a problem especially for higher values of N .

In general, a remarkable improvement can be achieved by combining both deterministic and stochastic approaches in the course of the R_A investigation procedure. Other approaches to the problem of R_A investigation can be found in [25] to [28].

5. Failure risks (hazards) analysis

Problems of risk of failures in every activity have attracted the interest of many people for a very long time. The possibility to fail concerns first of all the design, development and construction of artificial systems and of their alliances and it also concerns the people dealing with them.

Almost all contemporary advanced artificial systems and system alliances are very complicated and very often they form whole networks of system alliances involving a higher number of heterogeneous systems which follow either a common, but also sometimes partially divergent goal and for this purpose they are controlled and supervised by necessary alliance information tools (AIT), the role of which for the reliability of system or alliance operation was discussed above.

For simplicity, complicated systems and/or system alliances will be here called sometime only “Objects”.

Practically all such objects interact in a certain manner with human subjects (fully autonomous operation of some artificial system or system alliance appears only very exceptionally and when it does, this concerns mainly some relatively simple cases), either with individuals, groups or a community.

The interactions between the human subject and an object (artificial system or an artificial systems alliance) play a key role in almost any crisis situation in society. The proper and on-time human reactions are necessary even where human subjects operate, control or use particular objects or if they form only a part of the objects’ environment.

The factor of proper and on-time human reactions is of special importance also in all cases of human-terrestrial vehicle interactions, because vehicle driving or transportation system controlling activity requires high levels of attention for a considerably long time.

The same is true also with respect to interactions of pilots and flight dispatchers with the plane and with flight activities controlling systems, but also in operator interactions with target detection, identification and classification systems and their alliances, with fire and missiles guidance systems, in large financial operations, in complicated medical care, etc.

The term risk or hazard is unfortunately often used in various senses and achieving a common terminology still remains a challenge. Though scientists and practitioners have developed specific terminology for the assessment of particular hazards and impacts, this is unfortunately not precise enough and also not generally used. A more universal approach is required, e.g. for the purpose of EU guidelines encompassing a number of different fields of risks or hazards.

For the formulation of these EU guidelines, several international standards developed by the ISO (International Organization for Standardization), especially ISO 31000, ISO 31010, and the corresponding ISO Guide 73 terminology were used, in combination with the UNISDR (UN - International Strategy for Disaster Risk Reduction) terminology on disaster risk or hazard reduction.

Risk or hazard can be characterized in general as a dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of operation ability, loss of energy, loss of information, loss of livelihood and services, social and economic disruption, or environmental damage.

More precisely,

Risk (and hazard) is the probability that a certain object (system, system alliance or the whole network of system alliances) can fail in the period of its operation (D 2)

Between the terms risk and hazard, the use of which is often mixed, in more precise contexts risk is a combination of the consequences of events and the associated likelihood or probability of their occurrence resulting in the above mentioned object operation faults [31], where the probability of such fault events characterizing a quantitative measure of the risk is not too high, usually significantly below 50%.

Hazard, on the contrary, can be described as a highly probable occurrence of different fault intensities. Hazards can concern different areas, and can be estimated either from historical data or by scientific analysis [30]. The probability of operation failures in hazard situations is usually significantly higher than 50%.

Of course, boundaries forming the quantitative discrimination between risk and hazard are not sharp, the exact classification what is risk and from which level it has to be considered hazard is quite fuzzy (we exclude gambling games, which represent another field, in which the probability of loss for the gambling subject is considerably high, but in which on the contrary the probability of gain for the games organizing people or companies is very high – as far as is known for the slot machine, the probability of the gambler's win is less than 80%, i.e. they bring 20% profit, while e.g. in the whole Las Vegas gambling system it is about 93%, i.e. the profit is about 7%. In both cases the gambler pays the price for his pleasure from gambling).

In the field of risks and hazards some other terms appear. One has to distinguish at first between:

- actual hazard related to the probability of appearance of real failure events and
- latent hazard conditions, which may give rise to future failure events.

In [29] the following further definitions are recommended:

- Natural hazard is the high probability of a natural process or phenomena that may cause loss of life, injury or other health impacts, property damage, loss of livelihood and services, social and economic disruption, or environmental damage.

Natural hazards are therefore a sub-set of all hazards. In general, natural hazard events can be characterized by their magnitude or intensity, speed of onset, duration, and area of extent (see [30]).

- Technological hazard is hazard originating from technological or industrial conditions, including accidents, dangerous procedures, infrastructure failures or specific human activities that may cause loss of life, injury, illness or other health impacts, property damage, loss of livelihood and services, social and economic disruption, or environmental damage (see [30]).

When dealing with risks and hazards one has to take into account also other three important terms:

Exposure: Objects, i.e. people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses (see [30]).

Vulnerability: The characteristics and circumstances of a community, system or asset that make it susceptible (and sensitive) to the damaging effects of risks and hazards (see [30]). In probabilistic or quantitative risk assessments the term vulnerability expresses the percentage of exposure that is likely to be lost due to a certain risk or hazard.

Resilience: The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of risks and hazards in a timely and efficient manner, including preservation and restoration of its essential basic structures and functions (see [30]).

This last term is also sometime called resistance to faults or injuries.

As concerns the risk or hazard, the following additional terms are also used (look at [31]):

- **Risk (hazard) assessment** is the overall process involving risk (hazard) identification, risk (hazard) analysis, and risk (hazard) evaluation.
- **Risk (hazard) identification** is the process of finding, recognizing and describing the existence of risks.
- **Risk (hazard) analysis** is the process of comprehending the nature of risk (hazard) and determining the level of risk (hazard).
- **Risk (hazard) evaluation** is the process of comparing the results of risk analysis with risk (hazard) criteria to determine whether the risk (hazard) and/or its magnitude is acceptable or tolerable.
- **Risk (hazard) criteria** are the terms of reference against which the significance of a risk (hazard) is evaluated.

- **Risk (hazard) consequences** are the negative effects of a disaster expressed in terms of human impact, economic and environmental impact, and political/social impact.

When one deal with objects exposed to some risk or hazard one must expect some unfavorable impact on them. Because we cannot achieve 100% reliability of any object functioning for all intervals of considered independent variables, the probability of impact occurrence is in all cases higher than zero. As concerns the kind of impact, one can distinguish:

Human impact which is defined as the quantitative measurement of the following factors:

- number of fatalities,
- number of severely injured or ill people, and
- number of permanently displaced people.

Economic and environmental impact is the sum of the cost of cure or healthcare, cost of immediate or longer-term emergency measures, cost of restoration of buildings, public transport systems and infrastructure, property, cultural heritage, etc., cost of environmental restoration and other environmental cost (or environmental damage), cost of disrupting economic activity, value of insurance pay-outs, indirect cost on the economy, indirect social cost, and other direct and indirect cost, as relevant.

Political and or social impact is usually rated on a semi-quantitative scale and may include categories such as

- public outrage and anxiety,
- encroachment of the territory,
- infringement of the international position,
- violation of the democratic system, and
- social psychological impact,
- impact on public order and safety,
- political implications,
- psychological implications,
- damage to cultural assets,

and other factors considered important which cannot be measured in single units, such as environmental damage.

When discussing risks and hazards one has also to consider threat, which is a potentially damaging physical event, phenomenon or activity of an intentional and or malicious nature.

Risk (hazard) assessments determine the probability of occurrence of a certain risk (hazard) of certain intensity.

As concerns the structure of risk (hazard) assessment one distinguishes:

single-risk (hazard) assessments determining the singular risk (hazard) (i.e. likelihood and consequences) of one particular system operation failure or occurrence of a catastrophic event in a particular geographic area during a given period of time and

multi-risk (hazard) assessments determining the total risk (hazard) from several risks or hazards either occurring at the same time or shortly following each other, because they are dependent one on another or because they are caused by the same triggering event or hazard situations; or merely threatening the same elements at risk (hazard) (vulnerable and or exposed elements) without chronological coincidence.

Multi-risk (hazard) assessments determine the likelihood of occurrence of different hazards either at the same time or shortly following each other, because they are dependent one on another or because they are caused by the same triggering event or hazard, or merely threatening the same elements at risk (vulnerable and or exposed elements) without chronological coincidence.

These terms and factors are of special importance also in many aspects of transportation, especially as concerns high speed transportation on roads, rails, transportation of large volumes and high cargo and also all kinds of transportation in space.

It is well known that the decrease of human subject attention, his/her delayed reactions and incorrect decisions in interactions with transportation tools and systems cause daily very high risks and hazards and consequently very high losses, being the main reason for many transportation accidents.

These human factor influences are even more critical in the case of other kinds of crisis situation, because the operating or in the environment of the respective event acting human subjects are exposed to various stress factors and therefore their behavior can simply significantly differ from standard behavior.

Nevertheless, even in standard conditions, the human factor influence represents almost always the weakest point in all reliability and safety analyses.

In this part of our book, we focus further on five following aspects, which are of special importance:

- the character of contemporary artificial systems and system alliances and data structures representing them,
- possibilities of multidimensional data storing,
- possibilities of multidimensional data analysis and of mining the hidden knowledge,
- possibilities of multidimensional data representation for reliable interaction with the human subject,
- possibilities of multidimensional data prediction and diagnostics.

At first however, we mention some approaches to risk (or hazard) intensity evaluation.

According to [30], risks are the combination of the consequences of an risky or hazard event and the associated likelihood of its occurrence.

In many papers and presentations the risks and hazards taken as the probability to fail are often mixed with risks (or hazards) expressed as the product of the object value O_V multiplied by the probability of the fault event occurrence. Such a mixing causes, however, frequent misunderstandings.

Therefore here we distinguish:

Risks, hazards R probability [%]

Probable losses (damage) $P_L = R * O_V$ (5.1) [money, tons, m^3 etc.]

Dealing with real systems, one has remember that in the course of the objects exposure to risky or hazardous situation the risk (hazard) can change due to the influence of various independent variables, namely due to time t . Then the amount of probable losses cannot be expressed by a simple expression (26), but by

$$P_L = \int_{t=t1}^{t=t2} R(t)O_V(t)dt \quad (26)$$

where $R(t)$ is the dependence of risk (hazard) in the considered time exposition T_e and $O_V(t)$ is the dependence of the considered object volume in T_e .

Here at first the mutual independency of $R(t)$ and $O_V(t)$ is expected. However, in situations where the force of impact influences the likelihood of occurrence, i.e. where the two terms R and O_V are not independent of each other, the value of P_L cannot be expressed as a simple integral over a product of the two terms $R(t)$ and $O_V(t)$ but must be expressed as a complicated functional relationship. Likewise, where the impact is significantly dependent on preparedness or well made preventive activities, e.g. on in-time made prevention of the real threat, there are advantages in expressing the impact indicator in a more differentiated manner. In particular, in the analysis of natural hazards impact is often expressed in terms of vulnerability and exposure.

Vulnerability V is defined as the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of risk or hazard.

Exposure E is the totality of people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses P_L , for which holds

$$P_L = f(R * E * V) \quad (27)$$

Using the concept of vulnerability makes more explicit the fact that the impact of risk and hazard is also a function of the preventive and preparatory measures that are employed to reduce the losses.

For example, for a heat wave hazard it may be the case that behavioral preparedness measures, such as information and advice, can critically reduce the vulnerability of the population to the risk of excess death. Effective prevention and preparedness measures thus decrease the vulnerability and therefore also the values of P_L .

Depending on the particular risk analysed, the measurement of risk can be carried out with a greater number of different variables and factors, depending inter alia on the complexity of the chain of impact, on the number of impact factors, and also on the desired level of precision.

Generally, the complexity of the modeling and the quantification of factors can be increased as long as this also improves certainty.

Hence, when quantitative models and additional variables and factors increase

complexity without at the same time improving certainty (in terms of achieved reliability, prediction horizon and robustness) the use of more qualitative assessments and expert opinions will in principle be the better choice, also from the point of view of resource efficiency and level of transparency.

5.1 Contemporary artificial systems and system alliances and data structures representing them

We have already mentioned that the majority of present artificial systems get still more complicated, not only as concerns the number of their components, but especially as concerns the level of their complexity. Their structures contain many feed-back and feed-forward loops and often change quite dynamically in the course of time, but also in the course of changes of other independent variables of a different physical nature.

Nevertheless, the most complicated artificial systems operate usually as a system alliance (objects), consisting of a set of partial systems, the interaction and mutual cooperation of which is supervised by one or more alliance information tools (AIT). All the partial systems can have either their own inputs and outputs or two or more of them can share some common input/outputs ports (places in which external signals and stimuli can enter into the respective system or in which some output signal can be reached). Besides this, in the respective alliance structure, the AIT creates an area (one or more) where the general control activity is provided and where also the necessary general data are stored.

The basic general structure of a system alliance is shown in Fig.5.1.

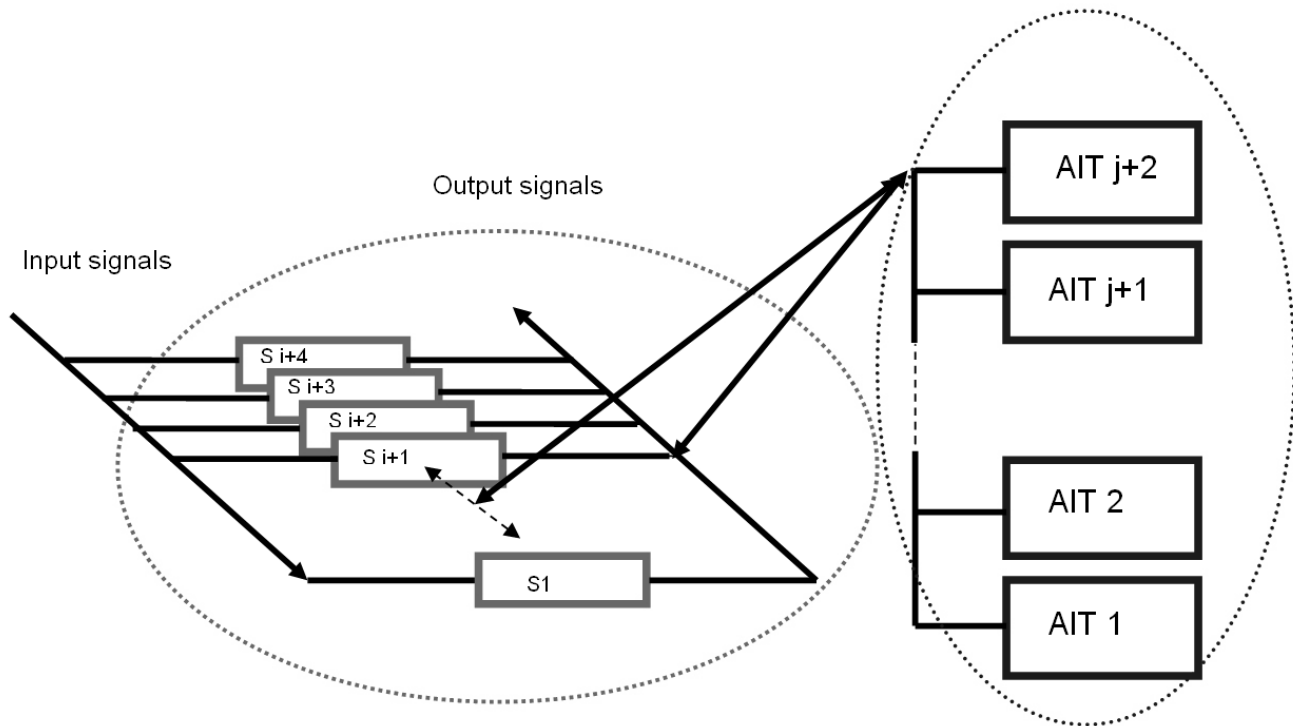


Fig. 5.1 General structure of system alliance: partial systems.....
partial alliance informa

The detail structures of system alliances can differ significantly, of course, being influenced namely by the kind and purpose of their operation.

The operation of all system alliances can, however, be expressed by the set F of N by them realized system functions F_k ,

$$F = \Xi \{F_k\}, k=1...K \quad (28)$$

The operator Ξ represents the actual kind of composition of partial system functions F_k into the set F , representing the properties and operation of the whole alliance.

Each system function F_k depends on three phenomena:

- the system structure S_i ,
- the vector X of system parameters x_i , $i = 1 \dots N$
- the vector of independent variables $P = \{p_j\}$, $j = 1 \dots J$.

As concerns the system structure S_i , this can differ in each partial system of the alliance, i.e. in general

$$S_{t1} \not\equiv S_{t2} \not\equiv S_{tk} \dots \not\equiv S_{tK} \quad (29)$$

This alliance has to be considered totally heterogeneous. However, quite often some of the K systems forming the alliance have identical structures, i.e. the respective alliance is only partially heterogeneous, or partially homogeneous.

Of course, in some cases one deals with totally structurally homogeneous alliances for which the inequality (5.5) does not hold at all.

Partial structural homogeneous alliances operate with a certain number of systems having identical structure which, however, can differ in values of their system parameters.

In the cases of structural heterogeneous alliances, for which (29) is true, the vector of system parameters X differs in its structure for each partial system of the alliance.

In the case of homogeneous alliances, where

$$S_{t1} \equiv S_{t2} \equiv S_{tk} \dots \equiv S_{tK}, \quad (30)$$

all the vectors X of partial systems parameters have the same structure, but they can differ in the values of their components x_i .

The system parameters x_i are supposed to have real values only (if they are vectors we suppose that they can be separated in real vector components).

Each component of a system vector value depends on independent variables P . The components p_j of independent variable vector P can be of various physical nature representing the influence of temperature, atmospheric pressure, humidity, level of radiation, electric or magnetic field intensity, gravity, etc. All these variables except one can be reversible, i.e. we can influence their values. The only exception is time $p_j = t$, which is absolutely irreversible. Time is the only absolute independent variable on which we have no influence.

This fact is very important for all system and system alliances reliability and life time, about which we shall speak later on.

Let us now consider the data structures representing the system and systems and system alliances properties.

In eq. (5.4) we mentioned the set F of K functions F_k which characterizes the properties of an alliance. This set can be quite heterogeneous as concerns the mathematical nature of involved functions F_k . Therefore, also the set of respective data representing these functions is expected to be heterogeneous.

This complicates the necessary analyses. Therefore we usually try to approximate the actual set of system or alliance functions F by some model set F_m , which is more convenient for analytical operation and for data storing. Of course, the condition that

$$F \ominus F_m \leq \Delta F, \quad (31)$$

where ΔF is the maximal allowable deviance of F_m from F , must be fulfilled.

The sign $\ominus$ represents here the distance between F and F_m in a K dimensional space, measured in the appropriate metrics. If possible, we chose for the model set F_m real functions F_{mi} depending besides the independent variables on the real system parameters x_i only. If we suppose that all these independent variables and the real system parameters exist in certain discrete values, the set $F_m(x_i, p_j)$ can be then represented by a multidimensional matrix $|F_m|$, having K subsets scaled by N sets of values x_i and J sets of values p_j .

Example of the hypercube matrix is shown in Fig.5.2.

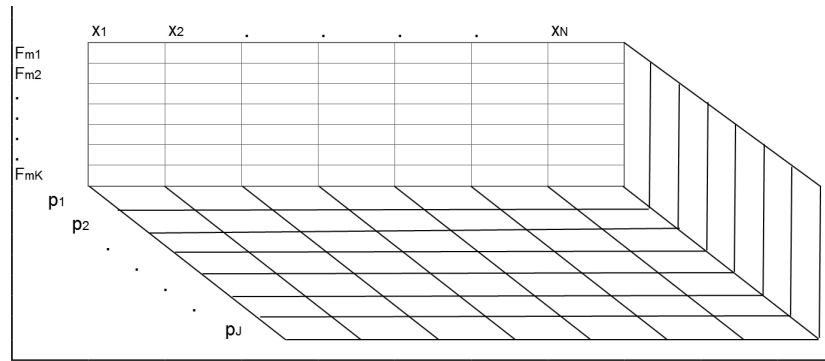


Fig. 5.2 Hypercube matrix of data representing the model set F_m

In the course of the alliance operation, the variances of independent variables p_j , forming in Fig. 5.2 the base of the hypercube cause the corresponding changes of parameter x_i values and also of F_{mk} values. These changes project in Fig. 5.2 by modification of data, involved in corresponding parts of the matrix $|F_m|$.

Evidently, in all cases of higher numbers K, N, J , i.e. in the case when one has to deal with more complex alliances consisting of many partial systems with many parameters and producing many system functions F_k , exposed besides time also to the influence of more other independent variables p_j , the storing of all necessary data requires to have ready

- a very large storage capacity,
- a very accurate system for identification of data positions
- a very effective system for searched data selection.

Therefore, the dimensions K, N, J of the chosen model F_m are recommended to be as low as possible, of course still with respect to the condition (31) in which reasonable allowable deviations ΔF must be accepted.

According to ISO 31010 ([31]), risks (and hazards, if the already mentioned distinguishing of these terms is respected) are the combination of the consequences of a risky event or hazard and the associated likelihood of its occurrence. Consequences are the negative effects of a disaster expressed in terms of human impact, economic and environmental impact, and political/social impact. More detail on the measurement of impact can be found in [29].

5.2 Possibilities of multidimensional data storing

In most practical cases however, the complexity of system alliances is very high.

Fig. 5.3 shows an example of a relatively simple system alliance, represented by the ESC system alliance, developed by Robert Bosch GmbH for position stabilization of modern cars (several other manufacturers produce similar systems). Such tools are very popular now.

The whole system alliance of ESC consists of 8 mutually cooperating systems; among them the first one has the role of AIT:

- Hydraulic modulator unit with attached ECU,
- Wheel speed sensor (in all 4 wheels),
- Steering angle sensor,
- Communication with engine management,
- Yaw-rate and lateral acceleration sensor.

Fig. 5.4 shows another example of a car assistance systems alliance, which was proposed as an EU project, but has not, unfortunately, been realized. Nevertheless, it is a good example.

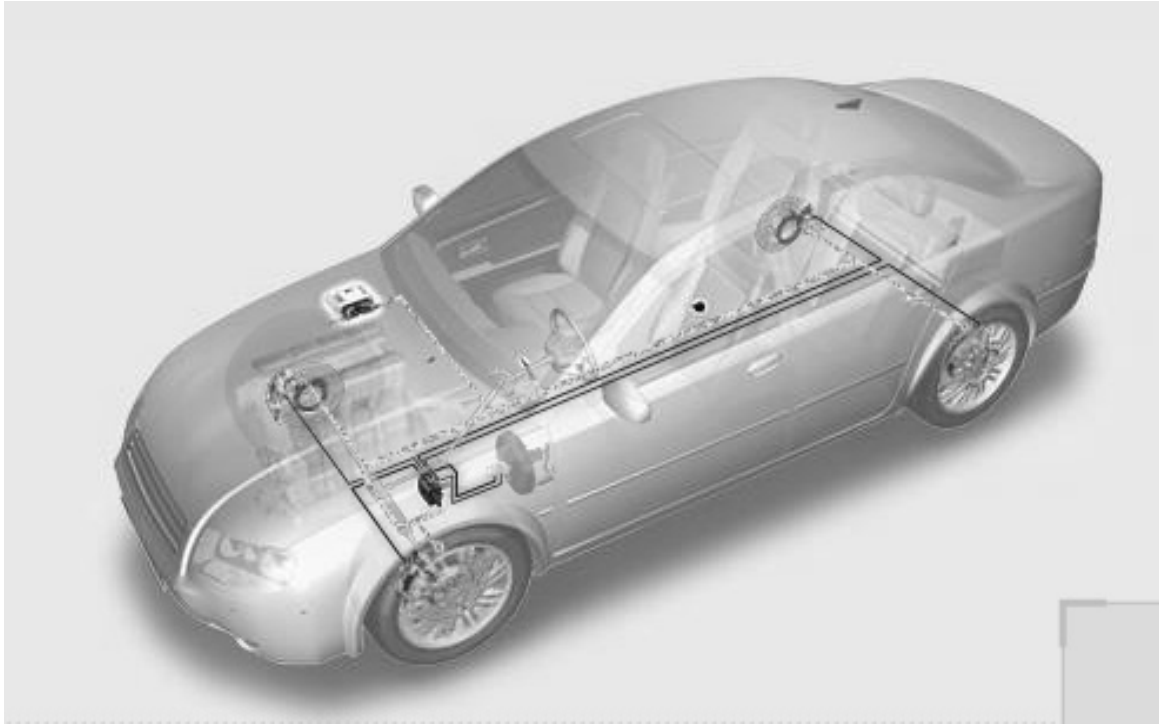


Fig. 5.3 Bosch ESC: the sensors constantly monitor the behavior of the vehicle and the driver's reactions. A central microprocessor analyzes the incoming signals and immediately triggers any needed action.

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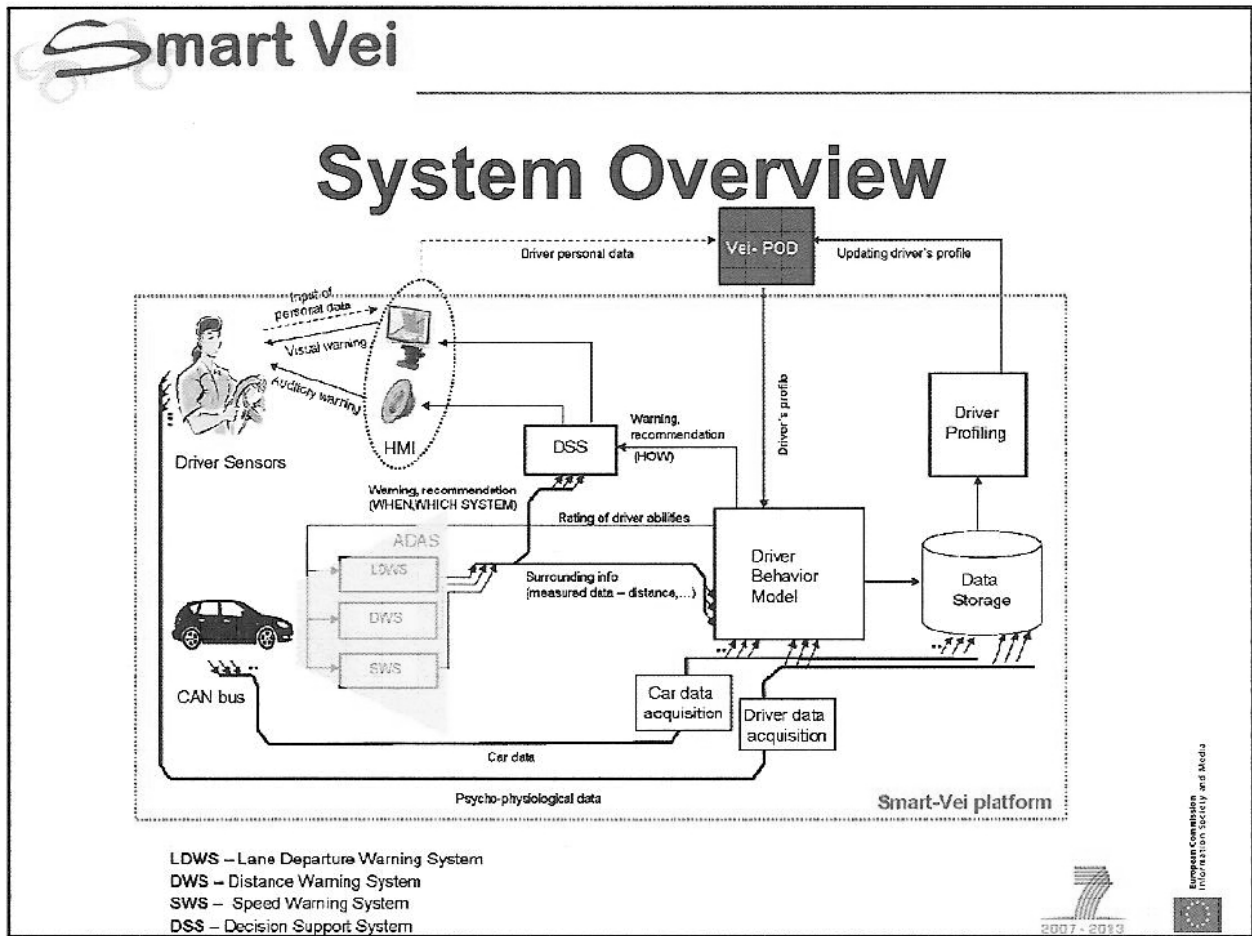


Fig. 5.4 Block structure of the car assistance systems alliance for warning the driver against lapses of attention, in the EU proposed but till now not further developed project Smart VeI.

Both these alliances are considerably simple, involving only 5 – 10 partial systems. In the case of the assistance systems alliance from Fig. 5.4, the roles of AIT are played by the block DSS and DBM (Driver Behavior Model) together.

At this point a significant difference between both of these alliance structures has to be mentioned.

In the case of the alliance from Fig. 5.3, the interaction with the human subject is realized in one place of the alliance structure, i.e. at the steering angle sensor. The driver has no other chance to influence this alliance operation, only by controlling the turning of the steering wheel. There can be some discussion if just a single detection of the steering angle is enough for the alliance's continuous operation. Some improvement can be seen in analyzing the steering wheel movement dynamics – the movement's speed, magnitude, accelerations and vibrations. One can expect that in more advanced alliances of this kind some of these aspects will be used.

As concerns the alliance shown in Fig. 5.4, more attention is paid to the driver.

In simpler applications, the dimensions K, N, J are considerably low and the respective data structures can be operated on with standard tools.

However, in some other cases the system alliances are much more complicated and can consist of several tens or hundreds partial systems. This is the case especially of air activities control system alliances. Similar problems appear also in alliances of systems for target analysis and in alliances of systems for space object collision prevention.

An example of a more complicated system alliance is shown in Fig. 5.5.

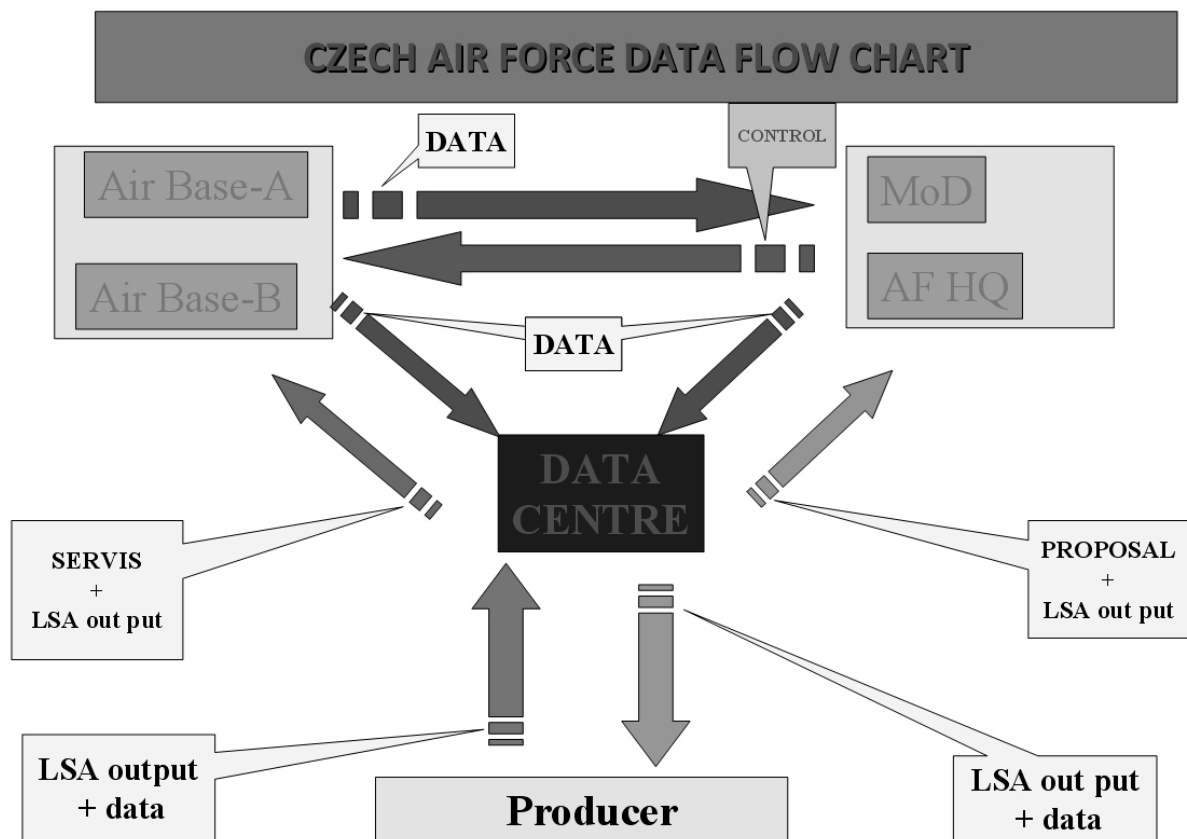


Fig. 5.5 Example of a complicated system alliance oriented to tribodiagnostics in the Czech Air Force

Here one can see some significant differences from relatively simple alliance structures, as shown in Figs. 5.3 and 5.4. First of all:

while there the interaction with one human subject only was realized, here the interactions are performed by more (eventually many) people in more (many) places of the alliance structure.

This is a very important factor which has to be carefully taken into account.

In the case of a system alliance interacting with one person only, as in the case of the alliance of car assistance systems of the type shown in Fig. 5.4, the individual character of this particular person influences all the interactions. Its eventual deviations from standard expected characteristics appear here quite naked, not masked or compensated for by any other human influence.

On the contrary, as concerns the alliance shown in Fig.5.5, the influence of interactions with the human subject can appear in more places of the respective alliance structure.

5.3 Possibilities of multidimensional data analysis and of mining the hidden knowledge

Fig.5.6 shows an example of multidimensional data with which one has to deal with in an alliance of systems for air activity control. As in many other cases these data are of heterogeneous nature, digital, visual, graphic and verbal. The human subject interacting with them needs a dynamic presentation of all of them, usually on a multi-screen display, as shown in the upper right corner of Fig. 5.6.

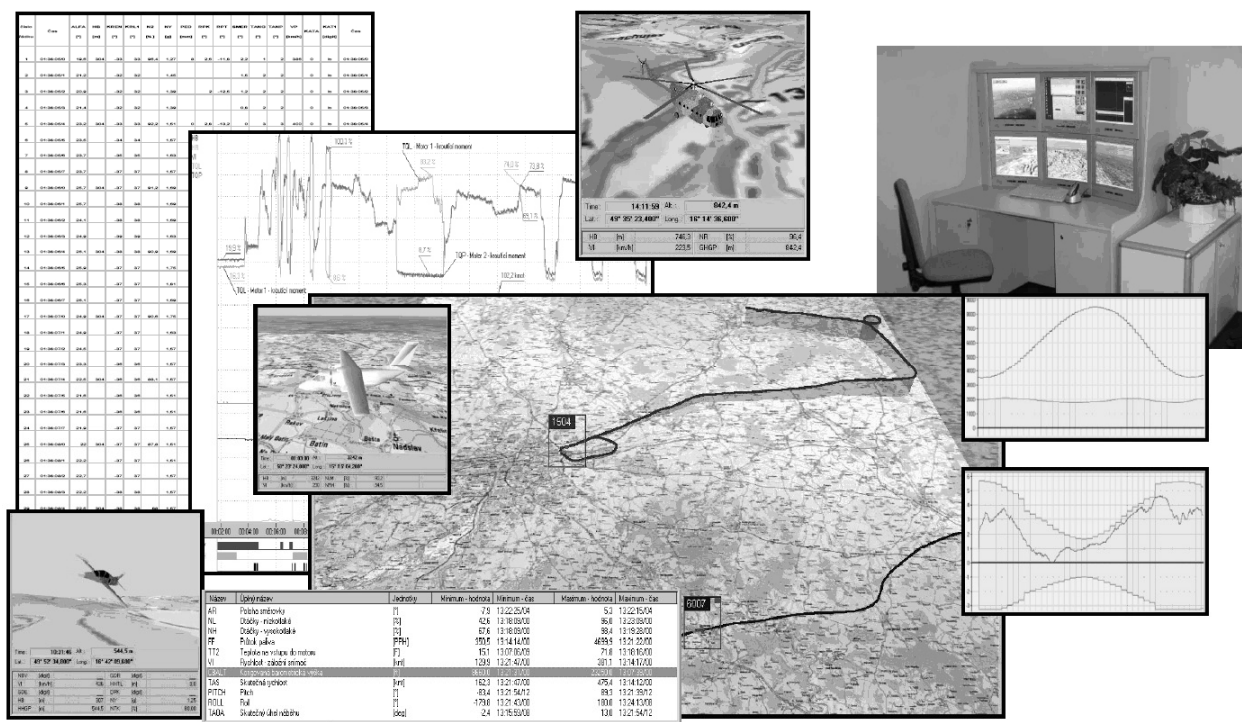


Fig. 5.6 Typical heterogeneous data

However, the interaction brings a set of additional requirements on the alliance controlling human subject. Besides the information sources well known from research concerning e.g. the reliable and safe car driving, here the operating person must follow several information sources almost at the same time. A good part of them is of visual nature. As it is known from neuropsychological investigations, the standard operator is able to follow more than one information visual source simultaneously only if they are located geometrically very near each other in his/her visual field. If the respective stimuli are more distant he/she has to switch attention from one to another. Of course, the discussion about this mechanism and the speed of switching is still open. Probably, for actual parallel observing of more visual stimuli, their angular distance should not be more than about 10° . Some neurophysiologist say that even in this case the number of stimuli is limited to 7.

For more angularly distant stimuli, the tested subject has to move his/her eyes or eventually the whole head. Both these movements consume time. This is a typical situation for the car driver moving his/her sight from ahead to one of the rear-view mirrors (schematic standard arrangement is shown in Fig. 5.7).

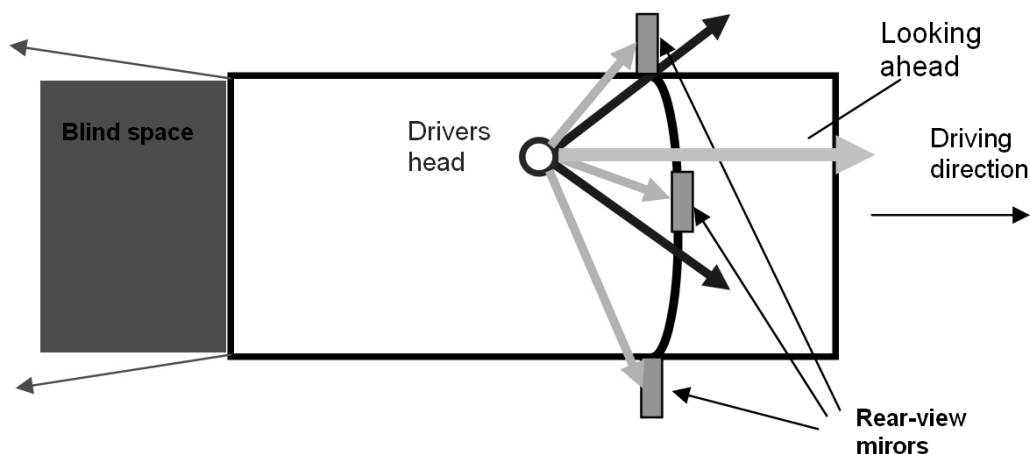


Fig. 5.7 Typical interaction arrangement of the driver with rear-view mirrors in the car cockpit

The considerably large set of measurements was made in the Joint Laboratory of System Reliability at the Institute of Control and Telematics, Faculty of Transportation Sciences, CTU, Prague on compact driving simulator especially equipped for such analyses (see Fig. 5.8, 5.9 and 5.10). The equipment Eye Tracker (see Fig. 5.11) was used for more precise measurements.

Some results achieved when measuring 8 different volunteers are shown in Fig. 5.12 – 19.

Here on the vertical axis are the response times volunteers need to divert their sight from looking ahead into looking in the rear-view mirror. On the horizontal axis are the performed experiments (at least 20 for each volunteer).

For all experiments

In Fig. 5.20 the table of mean values for all the 8 volunteers is presented



Fig.5.8 Equipment for observing the rear view in the right rear-view mirror of a compact simulator



Fig. 5.9 Left rear-view mirror and the view observed in it

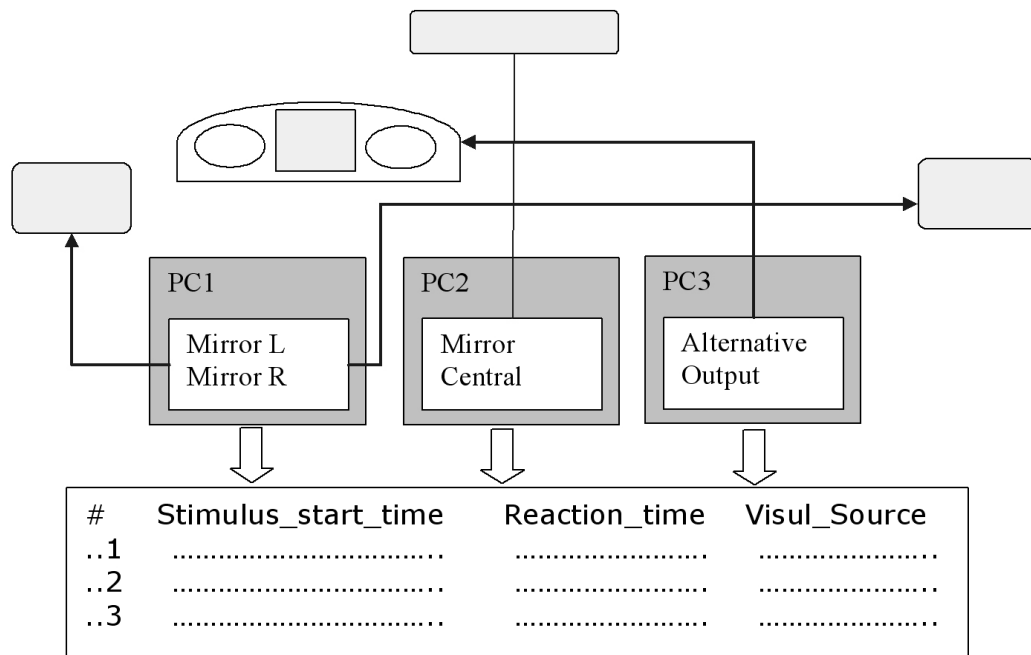


Fig. 5.10 Schematics of simulator arrangement for investigating attention splitting



Fig. 5.11 Eye Tracker helmet on a girl driver's head when tested on a car simulator

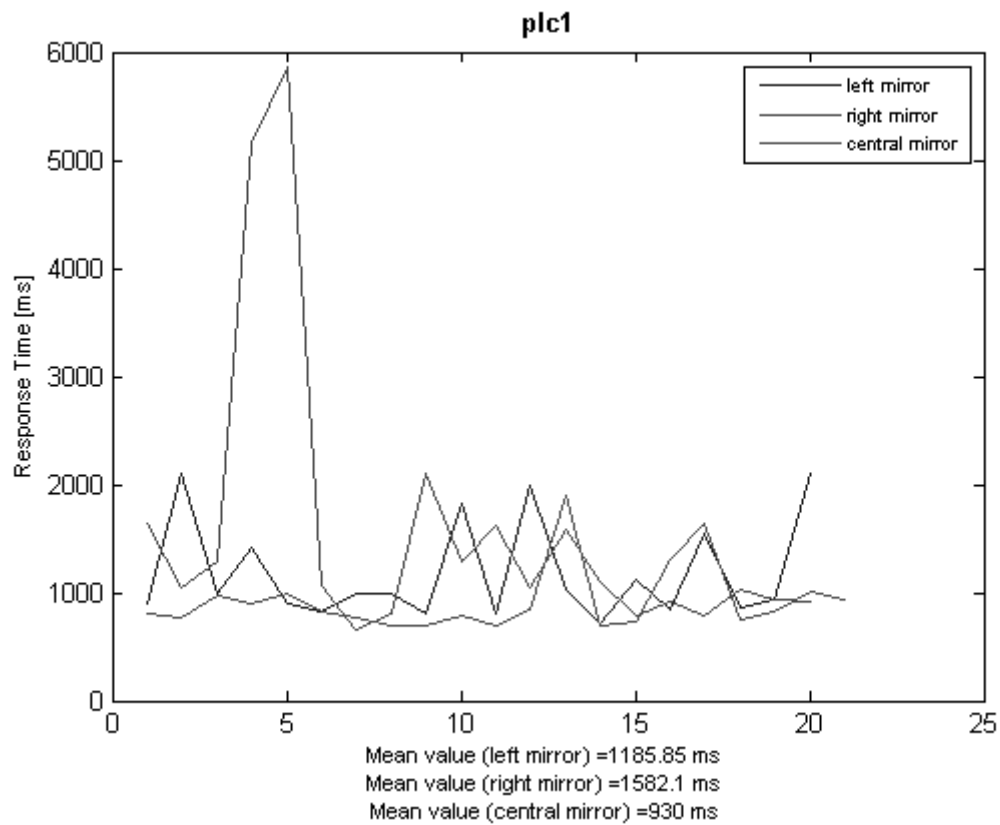


Fig.5.12 Response times of volunteer No. 1 necessary to divert the sight into rear-view mirror.

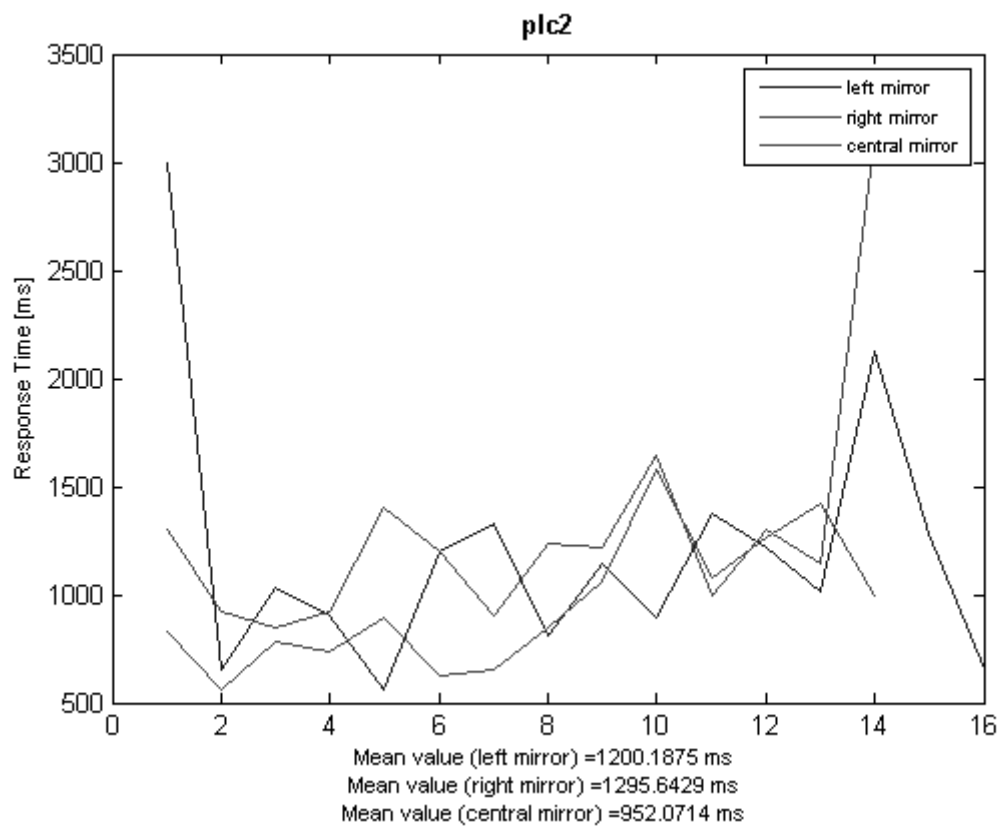


Fig.5.13 Response times of volunteer No. 2 necessary to divert the sight into rear-view mirror.

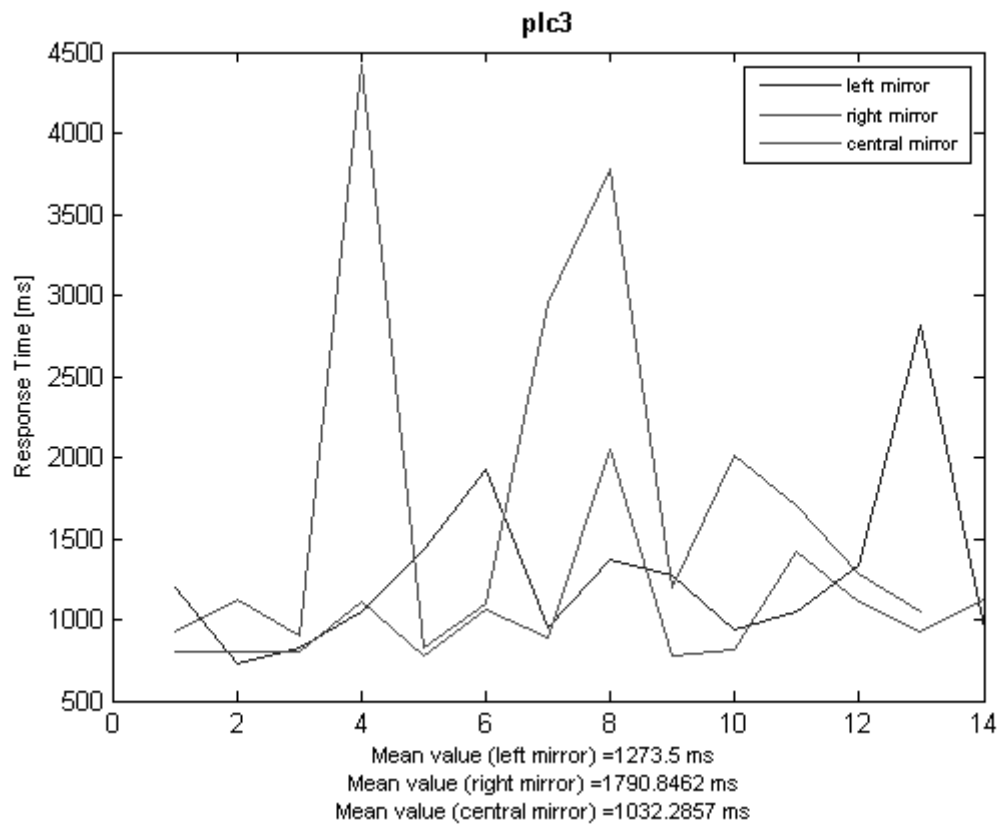


Fig.5.14 Response times of volunteer No. 3 necessary to divert the sight into rear-view mirror.

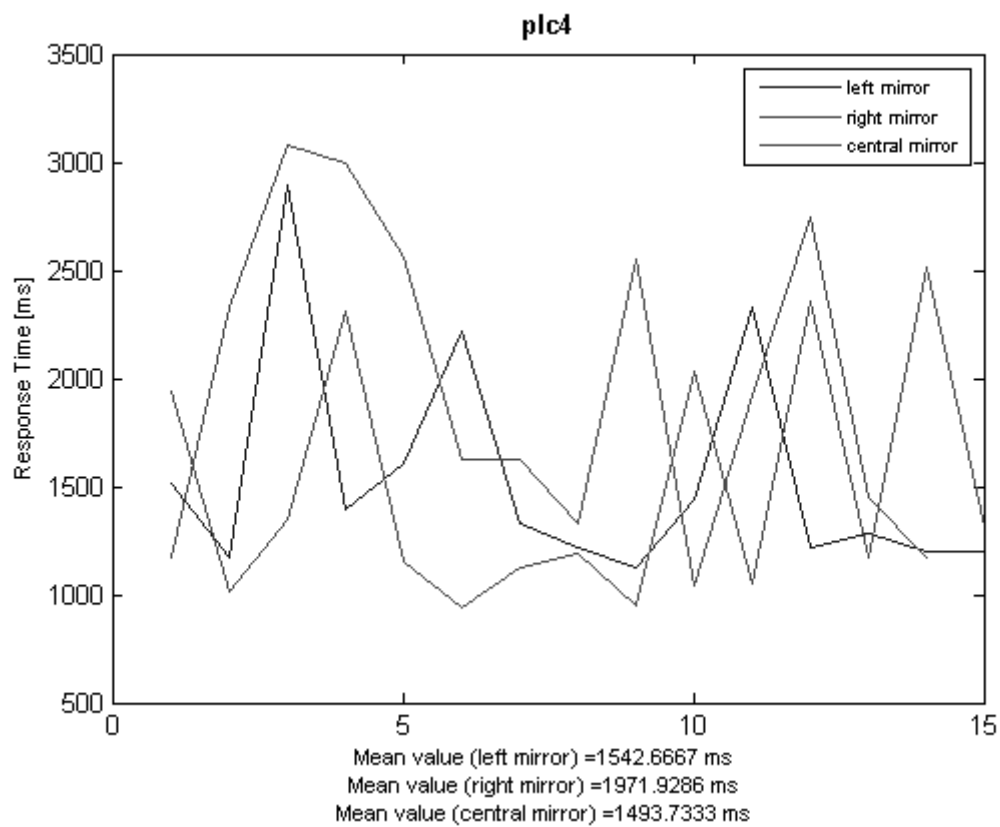


Fig.5.15 Response times of volunteer No. 4 necessary divert the sight into rear-view mirror.

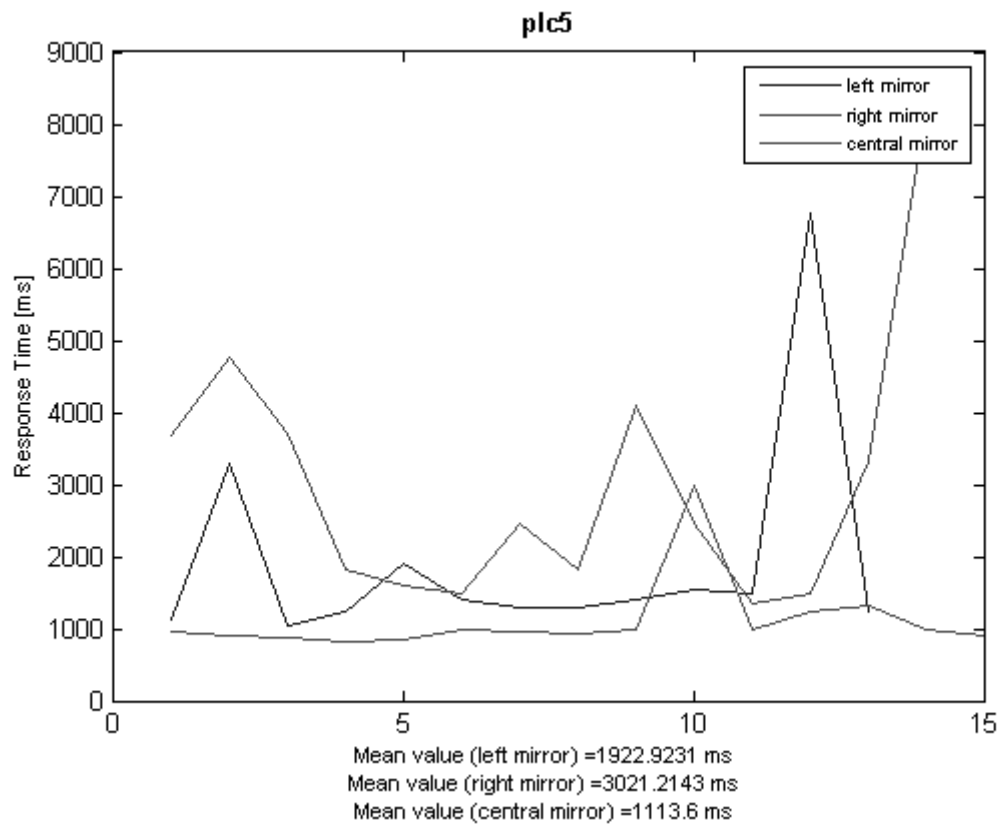


Fig.5.16 Response times of volunteer No. 5 necessary divert the sight into rear-view mirror.

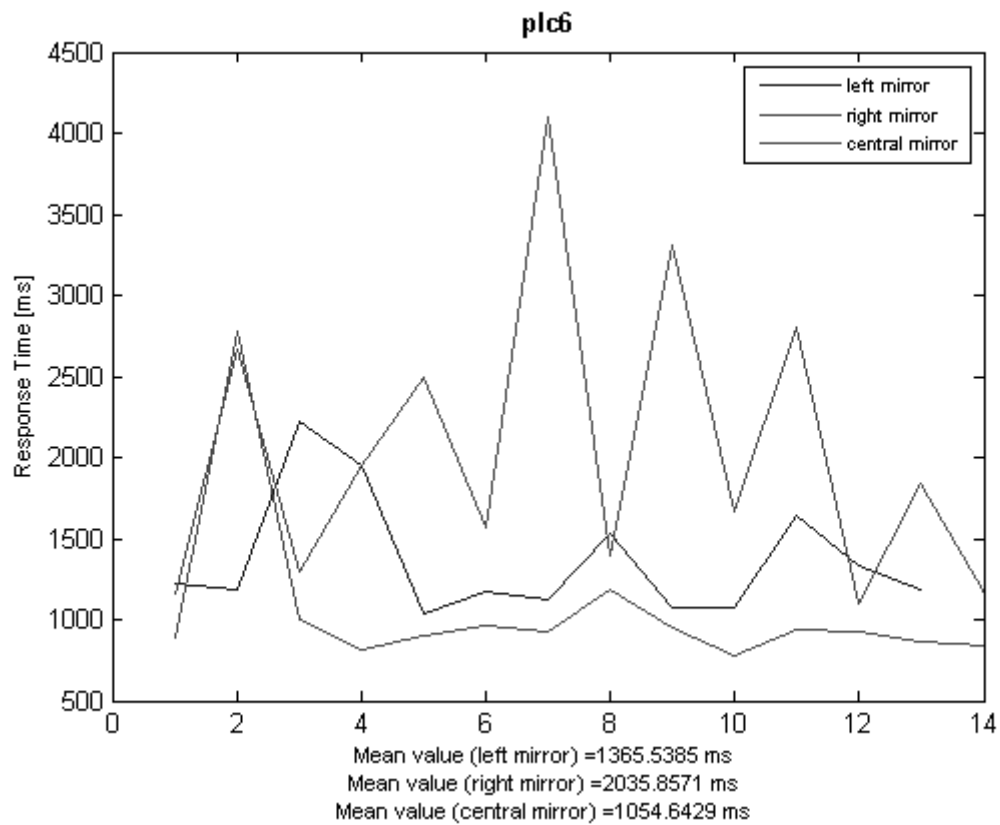


Fig.5.17 Response times of volunteer No. 6 necessary to divert the sight into rear-view mirror.

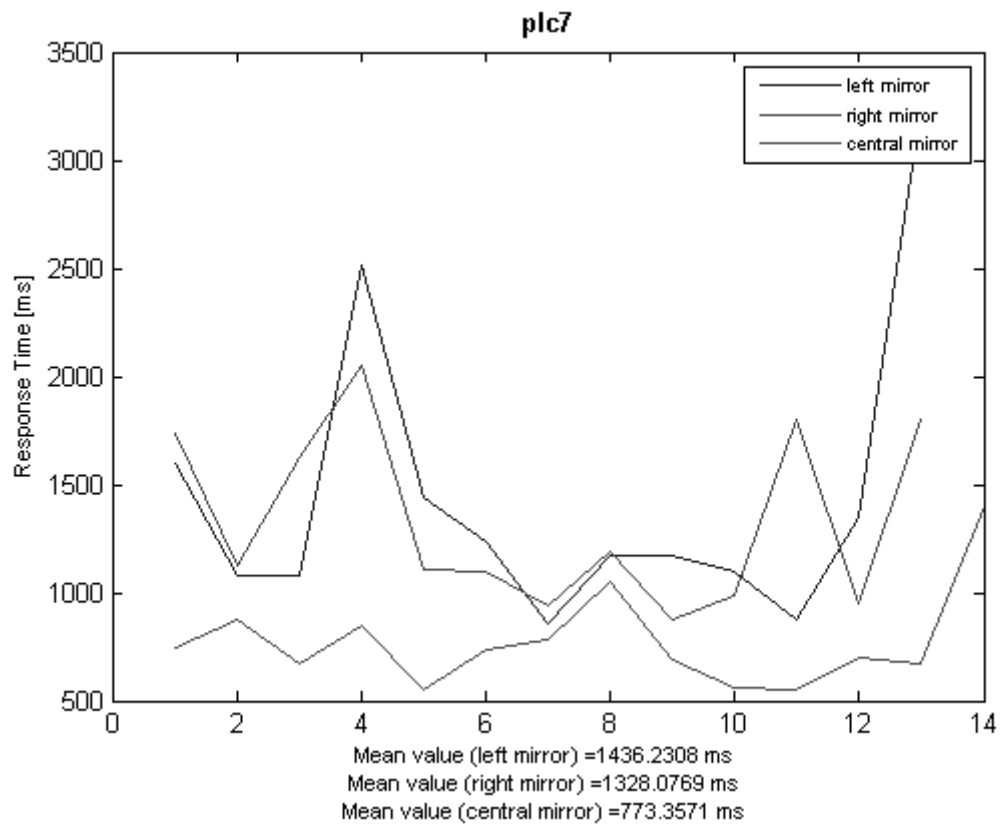


Fig.5.18 Response times of volunteer No. 7 necessary to divert the sight into rear-view mirror.

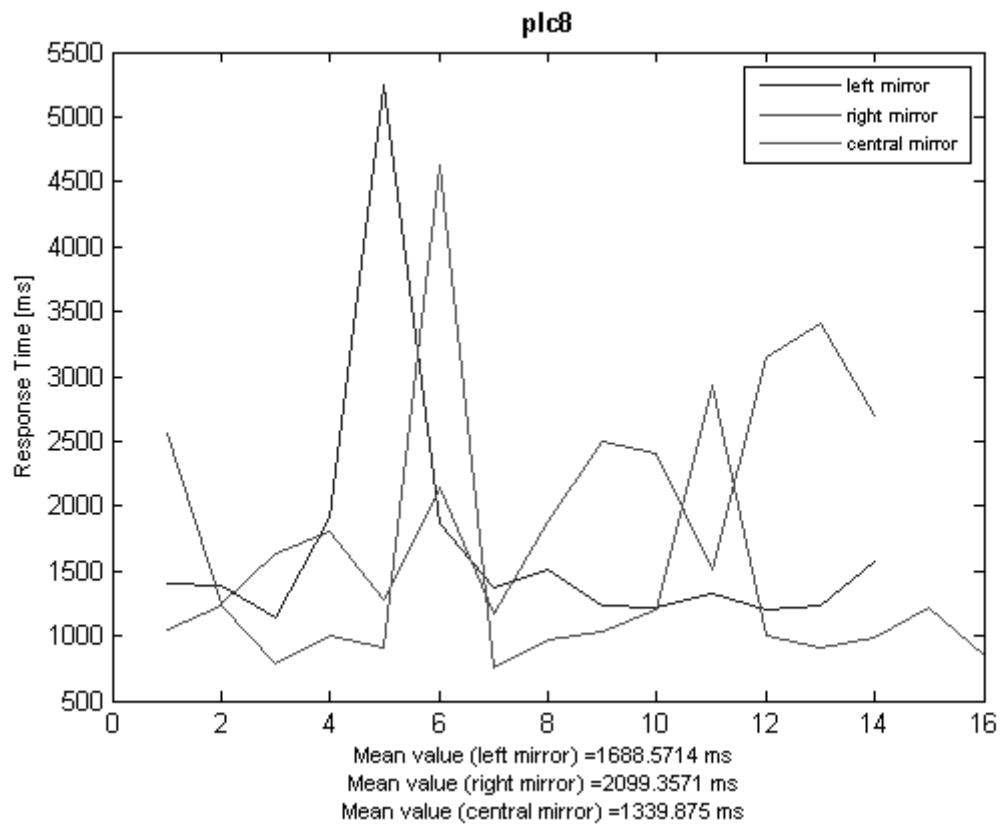


Fig.5.19 Response times of volunteer No. 8 necessary to divert the sight into rear-view mirror.

Driver	mean LEFT	mean RIGHT	var LEFT	var RIGHT
001	1025,00	1665,70	0,1797	0,7354
002	1323,40	2088,95	0,5214	0,6839
003	1218,70	1783,60	0,3144	0,8482
004	1264,00	1421,80	0,2181	0,3907
005	1184,45	1404,60	0,1676	0,3175
006	1057,80	1073,55	0,1915	0,1643
007	952,40	1532,80	0,1104	0,7097
008	1010,20	1402,30	0,2991	0,7086

Fig.5.20 Mean response times of volunteers' No. 1 - 8 necessary to divert the sight into rear-view mirrors.

Another important experiment concerning the driver's sight deviations from looking straight ahead was done by Novotný (see [4,12]). He tested a driver on the driving simulator presenting a virtual reality view of a tunnel road (in order to minimize the probability of looking aside). Results obtained by the instrument Eye Tracker are shown in Fig. 5.21.



Fig. 5.21 Frequency of a driver's sight deviations from looking straight ahead at the speed-meter situated on the cockpit panel. The measurements were done each 20 msec.

The red dots are the results of testing without internal illumination, the blue ones with it. Fig. 5.22 shows the histograms for measurement without internal illumination.

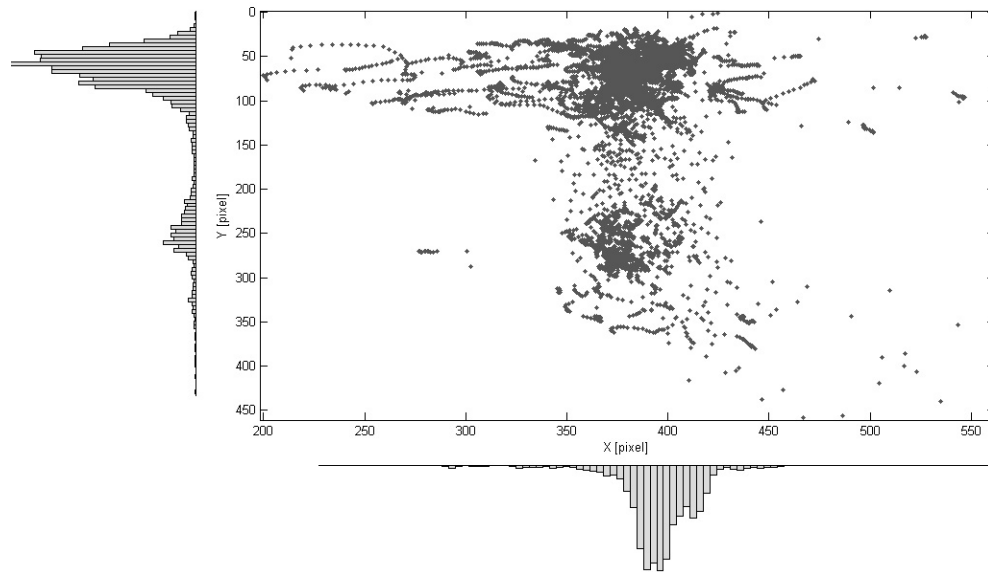


Fig. 5.22 Statistics of the driver's diversion from the view ahead while driving in road tunnel (simulated in virtual reality scenario)

In Fig 5.23 is shown the table with results.

	Volunteer No.:														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
[%] of glances at the cockpit panel without illumination	4,80	6,71	0,99	14,71	16,40	14,20	5,52	6,96	7,56	21,45	14,49	8,86	13,37	11,78	22,08
[%] of glances at the cockpit panel with illumination	7,08	6,62	3,00	10,41	13,52	8,54	3,98	4,77	5,31	15,05	12,24	8,05	9,71	5,33	27,76
Ratio of glances ahead to glances at the cockpit panel without illumination	0,05	0,07	0,01	0,17	0,20	0,17	0,06	0,07	0,08	0,27	0,17	0,10	0,15	0,13	0,28
Ratio of glances ahead to glances at the cockpit panel with illumination	0,08	0,07	0,03	0,12	0,16	0,09	0,04	0,05	0,06	0,18	0,14	0,09	0,11	0,06	0,38

Fig.5.23 Percentage of diversions from looking straight ahead. Due to requirements on data duality, only 15 from the 21 measured volunteers are included.

The tested volunteer group consisted of 21 people, 10 men and 11 women, aged 20 – 60. The length of the diversions was found to be about 40 to 200 msec.

From the table in Fig. 23 it is evident that, as opposed to the original hypothesis, the presence or absence of internal cockpit illumination does not have any significant influence on the ratio of diversions. However, the average length of diversions of more than 100 msec can be considered dangerous, if these are too frequent.

As concerns the glances into the rear-view mirrors, their average length was found to be much longer (see the table in Fig.20). This is the case of glances into the right mirror especially, where the length of attention splitting of about 1,5 sec must be taken as very dangerous and stimulating for tendency of development of another more advanced kind of transmission of the particular visual information to driver (e.g. on electronic base).

Unfortunately, even though some ideas in this respect have been proposed and though some experimental attempts exist (see [13] e.g.), till now the majority of car manufacturers prefer the conventional solution, even though it is evidently more dangerous.

The above mentioned results are of course not the complete solution of the reliability of driver – visual stimulus interaction problem. For this:

much more subjects need to be tested in order to eliminate the factor of human subject individuality,

besides the tested reaction times necessary for the driver's sight to divert from looking straight ahead to either the assistance systems indicators (here the speed-meter) installed near the top of the cockpit panel or to the three rear-view mirrors, also the influence of several other significant kinds of visual stimuli need to be investigated (various light signals, silhouettes of other cars, bicycles, pedestrians etc).

from all the received objective data the common factors have to be mined out. Only these can be later on used for eventual recommendations to cockpit modifications.

This is of course a task which needs a lot of detail measurements. These should be made in the environment of industrial research instead of the academic one, which should be more concerned with open methodical basis.

From the above mentioned information one can generalize that in the case of car drivers, the average diversions of the driver's sight from looking straight ahead to the cockpit panel causes attention splitting of about a few hundreds of msec, while the diversions to the rear-view mirrors can be about 1 sec and longer, which is evidently too long.

5.4 Possibilities of multidimensional data representation and analysis, especially for reliable human subject interaction

All analyses concerning the reliable and safe operation of complicated systems and system alliances and of their interactions with human subjects involve handling very large sets of heterogeneous data.

The spectrum of necessary kinds of data processing can be quite wide, nevertheless some are more significant, namely:

Signal analysis,

Time-series prediction (actually if we consider also another kind of independent variables besides time, one may have to deal also with other kinds of data series which can differ from time-series mainly in that the respective independent variable is not one-dimensional and one-directional. The well developed methods of time-series prediction are usually not accommodated for such cases.).

Mining of information and/or knowledge hidden in large sets of heterogeneous and dynamically variable data (the term of dynamics is usually considered mainly with respect to time, but in general at least some part of stored data can be dependent also on some other independent variable besides time).

Estimation and analysis of regions in which the considered object parameters can vary

If the data are analyzed a posteriori, after their measurement or after the respective object operation, when there is enough time for employing the necessary procedures, the majority of the analytical methods are satisfactory. This concerns both the signal analysis and the data mining.

Problems appear, however, if the size of the respective data sets is too large, if the processing has to be done in almost real time and if the requirements on processing accuracy are high. This is usually not the case of car – driver interactions, but in aviation and even more in space applications the situation can be completely different.

For operating with extremely large and complicated sets of data and for their processing, storing and analysis (actual and a posteriori) it is not possible to use contemporary methods only, but it is necessary to develop new correspondingly powerful approaches, methods and tools.

This concerns especially experimental data analysis where quick recognition of the hidden information and knowledge in these sets has fundamental significance for reliable classification of the actual situation and finding the correct operation decision.

In general, similar tasks appear also in the field of defense systems, advanced medical systems and economical systems. Also here the necessary methods must fulfill the incompatible requirements on size of processed data sets and high speed of processing.

An important approach to solution of these problems can be found in prediction diagnostics, a methodology developed recently for solution of system reliability problems, which allows to estimate in which part of the considered object a failure can be expected, what is the nature and significance of respective data changes, what

their negative effects can be and when they can appear, what can be the recommendable optimal restoration procedure for fastest and cheapest restoration and replacement of the system's abnormal state. Besides this, this methodology can deal also with problems of prediction, what is the probability of the system's failure under actual or expected operation conditions.

Similar methods have been investigated in the system and reliability theory for some time with good results, however, not under the high requirements brought about by their application in space transportation.

For these new and difficult conditions they have to be modified significantly and probably quite new approaches have to be found (see [42] , [43] e.g.).

The following aspects have to be respected for this purpose:

- the ability to deal with a wide spectrum of data kinds: numerical, graphical, visual, acoustic, etc,
- the ability to work with very large data bases,
- the necessity of very fast solution – the time available for processing can be rather short,
- the necessity of very accurate results,
- the ability to predict the development of observed situations for long prediction horizons.

Though the use of powerful computer technology can simplify these problems, there are many applications where this possibility is limited, mainly due to cost or parameters and mass of supercomputers. Something can be achieved by the use of remote (distant) task processing of solved tasks on these powerful tools. In these cases only the input data and results are transmitted, but still the transmission speed and reliability represent a serious limitation.

In probably a bit more distant future, a significant progress in computing power and processing speed can be expected from the application of principles of the so called quantum computing. However, at the moment it is quite hard to estimate the time when this technology will move from laboratories to practical applications.

Another way is using advanced task models. Actually, when dealing with any task, one at first has to find the appropriate model. This must, though being simple enough, describe the modeled object operation with high enough accuracy. For example, in describing object trajectory and movement dynamic, a simplification by its spectral decomposition can be used. The simplification consists in neglecting higher spectral components. Because, as is well known, the standard Fourier methods based on decomposition in a set of harmonic functions are not suitable for dealing with quasi-periodic and quasi-stationary processes, alternative approaches are used. They are many and the optimal one for a particular problem has to be carefully chosen. Some interesting results can be achieved on the base of operation with Zolotareff functions, as shown by very promising numerical experiments of Prof. M. Vlček at FTS CTU, Prague and his research group. Some examples of these results are shown in Fig. 5.24 and 5.25, see [46],[47] e.g.).

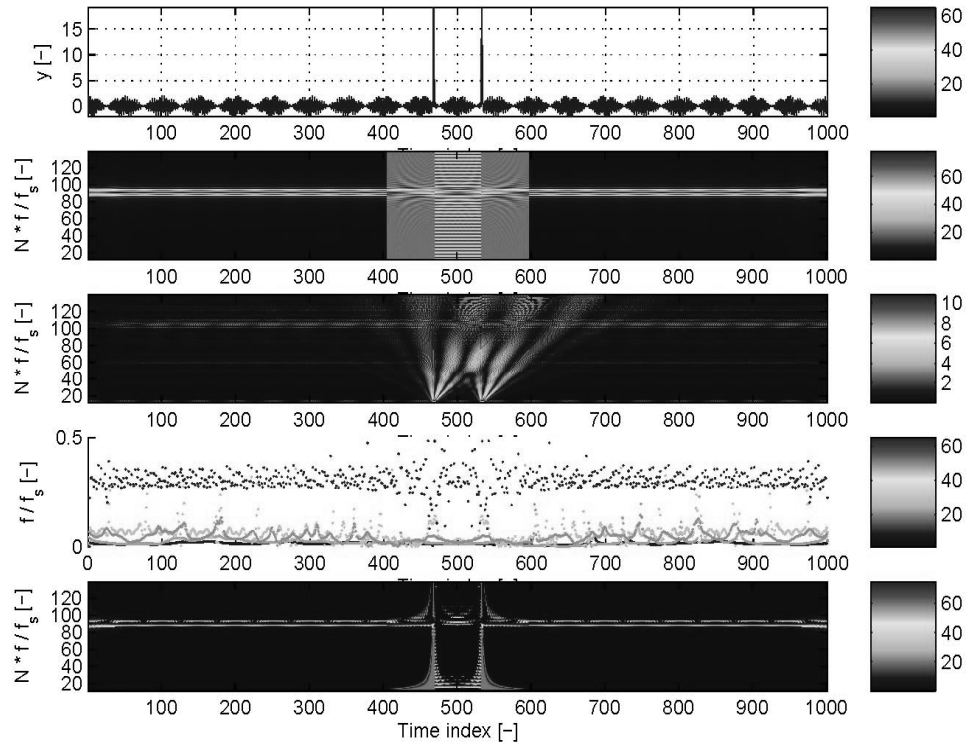


Fig. 5.24 An excerpt of a voice signal and its highest energy component computed using Discrete Fourier Transform - DFT, Principal Component Analysis - PCA, and Discrete Zolotarev Transform - DZT.

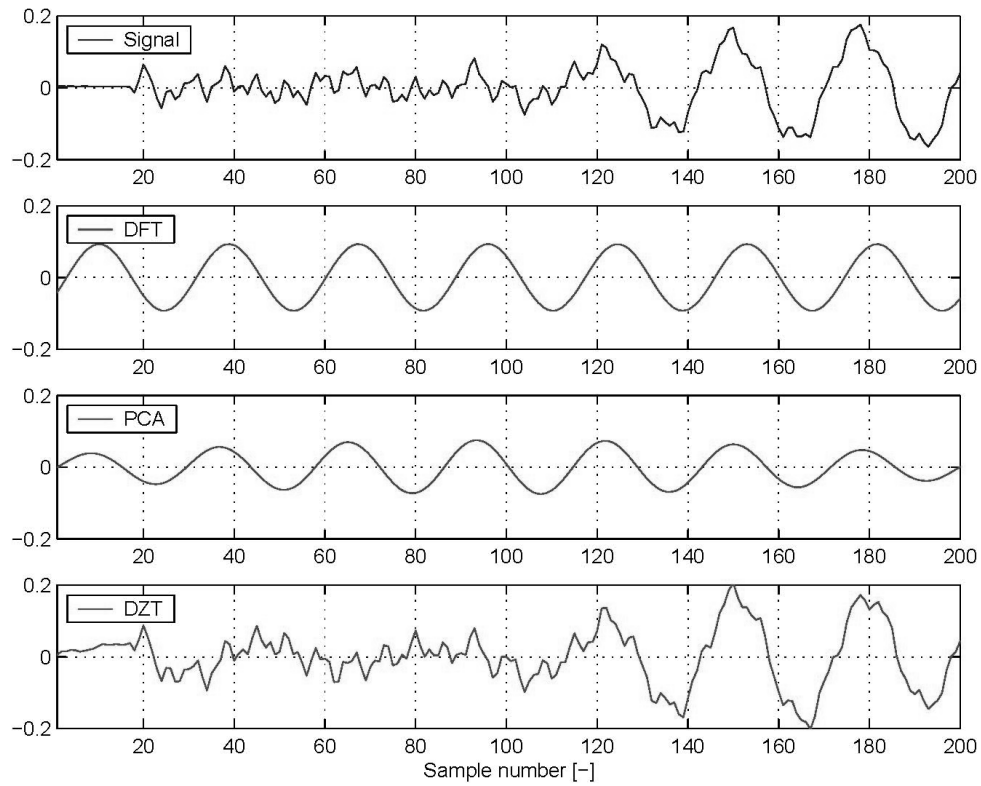


Fig. 5.25 Sum of two discrete cosines and twenty times scaled Dirac impulses. STFT spectrogram, rectangular window $N=128$, padded by 64 leading and 64 trailing zeros. WT, Meyer mother wavelet. HHT. DZT hologram, rectangular window $N=128$, padded by 64 leading and 64 trailing zeros. The extremely good correspondence between original signal and DZT is evident.

In general, a well chosen model can allow the respective object properties' description with acceptable accuracy obtainable in reasonable time.

A lot can be also achieved by using high level parallel processing. A well made decomposition of the problem into a set of partial tasks which can be solved in parallel can significantly speed up the necessary processing. While the classical parallel processing is concerned usually with a relatively small number of parallel processed partial tasks, much can be achieved by using a really mass parallel processing, like the one realized by artificial neural networks (ANN). Here the actual parallelism can reach the number 10^5 and more. Of course, one has to take into account that, typically, the construction and training of ANN is a long lasting task. However, its response calculation can be extremely fast, especially if the respective ANN is hard-ware realized (e.g. by field programmed gate arrays – FPGA). For a successful application of the approach, of course, another set of problems has to be solved, e.g. the sensitivity of ANN transfer function to its parameter changes, the ability of trained ANN to modified tasks, the stability of a complicated ANN if its parameters vary, etc.

The reliable and safe function of all transportation vehicles and systems depends not only on keeping their technical condition at an acceptably high level, but also on reliable and safe interactions of these transportation tools and systems with human subjects.

This is true in general, but with regard to aviation and especially space transportation the significance of human interaction factor increases much more.

The human subject interacts with transportation tools in the following three main areas:

- as their designer and creator,
- as their operator and supervisor,
- as their user.

In all these cases the insufficient reliability and safety of the human subject leads with a very high probability to large, often fatal failures resulting in serious economic and/or health losses. Therefore, more knowledge on HMI (human – machine interaction) would be desirable.

This concerns especially

- the investigation of human subject reaction to impacting stimuli (visual, acoustic and other),
- the human ability to react fast and with high enough probability of correct response, the human ability to store a large enough amount of information for a significantly long time,
- to select the proper of them and
- to mine and use the necessary knowledge.

Similar importance has to be given also to problems related:

- to limitations of the human subject's level of attention,
- to the process of attention decline over time and due to various humoral and environmental influences, and
- to methods and tools for improving human resistance to such limitations and decline.

The size and scope of the problems mentioned in this part of our book is evidently very wide.

For their successful solution a deep knowledge not only from:

- system theory,
- reliability theory,
- signal theory

is necessary, but also from

- brain science (and its special part called now neuroinformatics),
- informatics,
- medicine and
- transportation science

in general.

Though it is evidently not possible to include all the relevant knowledge in one book part, we will try to mention in the following paragraphs the most important parts.

6. Prediction diagnostic in multi-parameter systems

The successful prediction diagnostics requires efficient estimates of the object's future trajectory, i.e. in the acceptable distant prediction horizon.

The term future is here meant usually as the coming situation in time. However sometime it can also means the state at a distant stage influenced by change of other independent variable. Nevertheless, in this part of our book we focus on the prediction in time sense.

The process of estimating the future expected stage of some event is relatively well developed and is known as time-series prediction.

As concerns the prediction diagnostic, the prediction procedure is here applied before and on the shape of the so called life curve, under which term we understand the trajectory of the vector $X(P,t)$ when t changes (in some cases also the eventual changes of other independent variables P can be considered, but in almost all cases the interest of time dependences dominates). If one starts to observe some object properties represented by the set of its system functions $F(V, P, t)$ at the time $t = t_0$, the changes to some time $t = t_k$ cause the movement of the vector of system parameters X from the point X_0 to the point X_k , see Fig. 6.1. This change is done along the trajectory $\Psi(t)$. - the life curve.

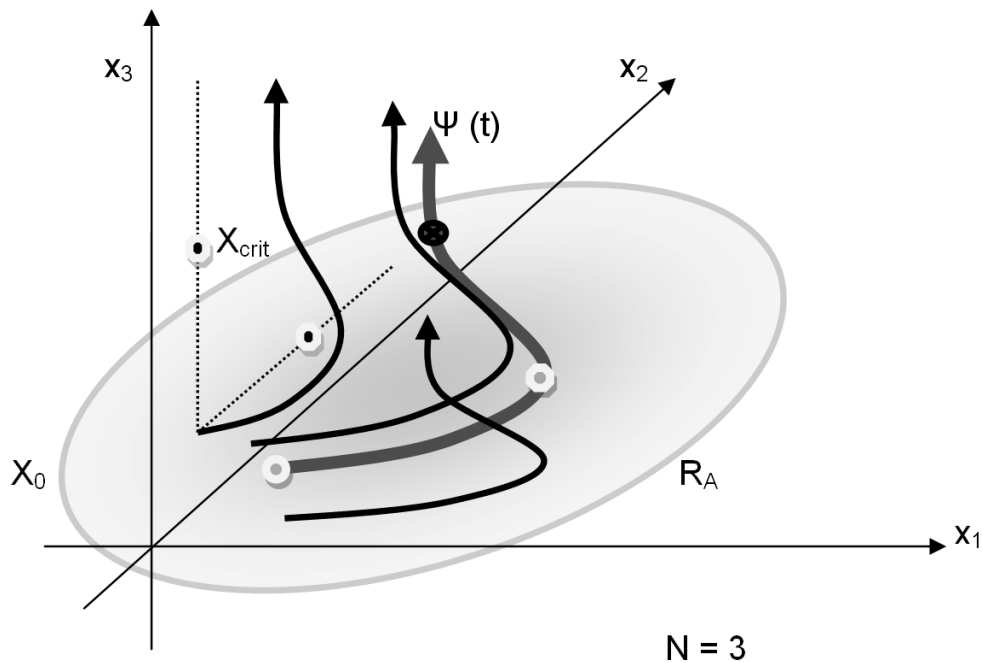


Fig.6.1 Changes of the life-curve $\Psi(t)$ during course of time t for $N=3$ and its projections in two dimensional planes (thin black curves). Point  indicates the beginning of the life curve, point  indicates the place where at time t_{crit} the boundaries of R_A are broken.

The life curve starts in the point X_0 at the time $t=t_0$. If it remains inside R_A the system is able to operate well. However, corresponding to Theorem 4.1, at a certain time t_{crit} it must leave R_A . This happens in the point X_{crit} at the time t_{crit} .

If the actual situation of the considered system can be characterized by some point on curve $\Psi(t)$. lying inside R_A (the green dot on the red curve in Fig. 6.1 e.g.), we are very interested in estimating how long the travelling of X from this particular actual position to X_{crit} will last, i.e. what is the expected system's lifetime. Therefore, if we know the trajectory $\Psi(t)$. from X_0 to this actual point  we must predict the remaining part of $\Psi(t)$. to X_{crit} (and even further).

This is the task of time-series prediction.

If one knows the dependence $X(t)$, the trajectory $\Psi(t)$. can be determined directly as the geometrical place of points X for various values of t , from $t=t_0$ to infinity. In this there are no principal problems. What can be

difficult is the finding of the point X_{crit} . The distance of X_{crit} from X_0 measured along the respective part of $\Psi(t)$, determines the particular system's life-time T_1 .

Unfortunately, the standard well known time-series prediction methods operate well mainly for one dimensional cases. In the majority of investigated systems, $N \gg 1$. As is demonstrated in Fig. 6.1, from the knowledge of one-dimensional predictions one can only estimate the real position of X_{crit} in an N dimensional space only with difficulties. For determination of X_{crit} one can use a suitable combination of methods for investigation of the regions of acceptability R_A in the direction of $\Psi(t)$. However, this can be quite laborious, especially if there are many strong correlations among the $X_i(t)$.

In certain cases, the prediction of the trajectory $\Psi(t)$ shape needs to be extended behind the point X_{crit} outside the region of acceptability R_A . These are the cases where we are interested in corrections of already operating reliability failing systems.

Here we have to start the correction (restoration) procedure in some point $X_{t_{corr} > t_{crit}}$. Usually, long delays of restoration start are not advantageous, because time flows independently and in majority of cases the distance of the actual position $X(t)$ from X_{crit} increases with the distance between X_{crit} and the actual position X on $\Psi(t)$.

With respect to this distance, one can distinguish two main kinds of restorations (repairs).

a) Early repairs, started considerably early after the life-curve $\Psi(t)$ breaks the boundaries of R_A .

b) Delay repairs, started significantly later.

The procedure of repair is done in the X space along the so called repair trajectory $\Psi_{rest}(t)$. In the case of early repairs the point $X_{rest\ st}$, from which restoration procedure starts, is not too distant from X_{crit} (see Fig.6.2). Then it is quite probable that the restoration expenses will be not too high and that also the restoration time will be considerably short. The restoration trajectory $\Psi_{rest}(t)$ (the violet curve) starts from a point not too far from R_A boundary. If the restoration procedure has the "slight" nature, it stops soon after the return of the point X inside R_A . Of course, the second life-curve of the restored system can be in this case quite short (see the dotted red line in Fig. 6.2).

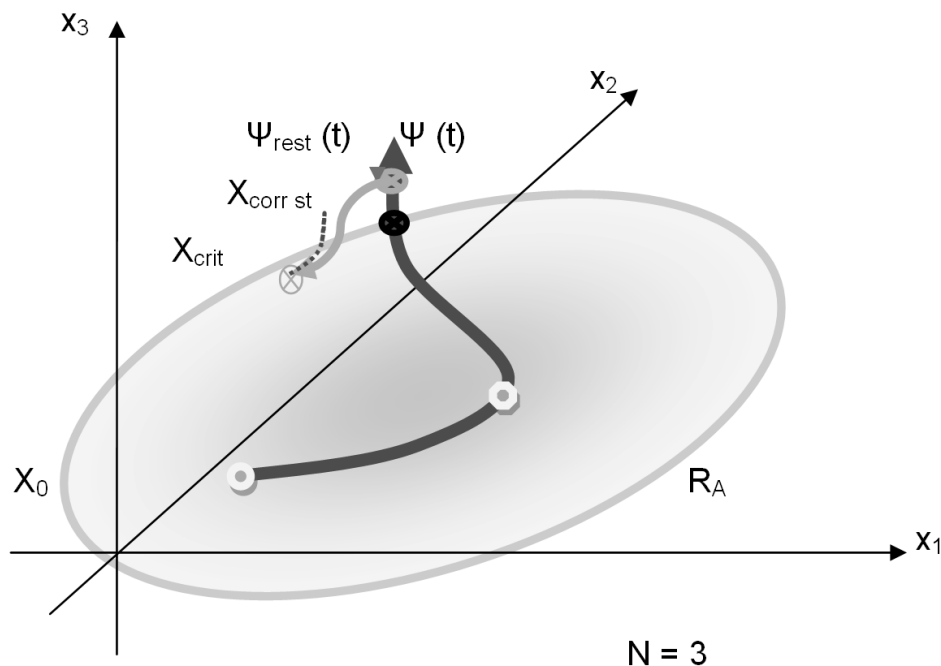


Fig.6.2 Here the point $X_{corr\ st}$ is shown, located considerably near to point X_{crit} on the life curve $\Psi(t)$ outside R_A . From here the "early" restoration trajectory $\Psi_{rest}(t)$ (the violet curve) starts. If the restoration procedure has the "slight" nature, it stops soon after the point X 's return inside R_A .

If, however, the restoration procedure is started considerably late, the point $X_{rest\ st}$ can decline from X_{crit} much more because of other post-failure degradations of X parameter values, and therefore the "late" restoration procedure will last in such a case longer and will be also more expensive (see Fig. 6.3). One can roughly take the distance between X_{crit} and $X_{corr\ st}$ measured along $\Psi(t)$ as the figure of merit of restoration time

and expenses. Of course there are cases in which some of the post-failure parameter X values degradations can be frozen, e.g. simply by putting the failed system out of operation. However, principal degradations caused by not-removable time changes still exist.

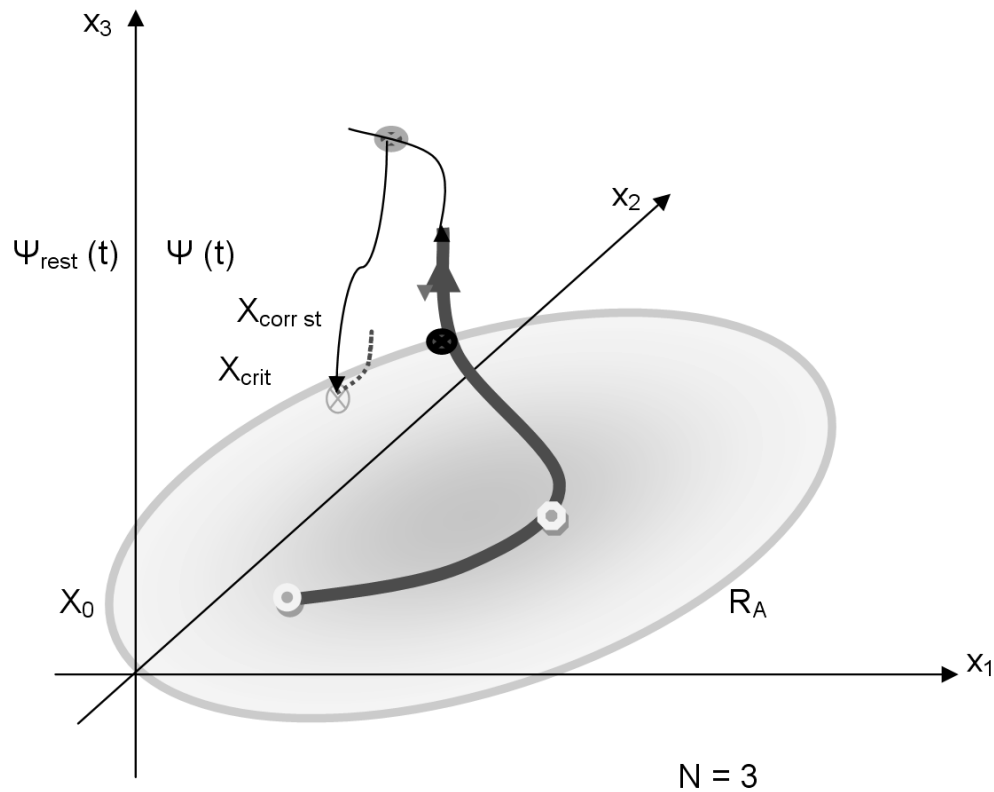


Fig.6.3 Here the point $X_{corr\ st}$ is shown, located considerably far from point X_{crit} on the life curve $\Psi(t)$ considerably far outside R_A . From here the “late” restoration trajectory $\Psi_{rest}(t)$ (the violet curve) starts. If the restoration procedure has the “slight” nature, it stops again soon after the point X ’s return inside R_A .

These repairs classification can be completed also by respecting the repair target.

In cases of the so called slight repairs one stops the restoration procedure very soon, just after the point X ’s return inside R_A , as shown in Fig.6.2 and Fig.6.3. These repairs can be fast and cheap, but the durability of the repaired system is usually considerably small.

On the other hand, heavy repairs have the target of the restoration procedure deep inside R_A , usually near X_0 (or sometime behind X_0 in the negative direction of $\Psi(t)$ development – the so called predistored repairs, whose life-time after repair can be higher than the original one), see Fig. 6.4.

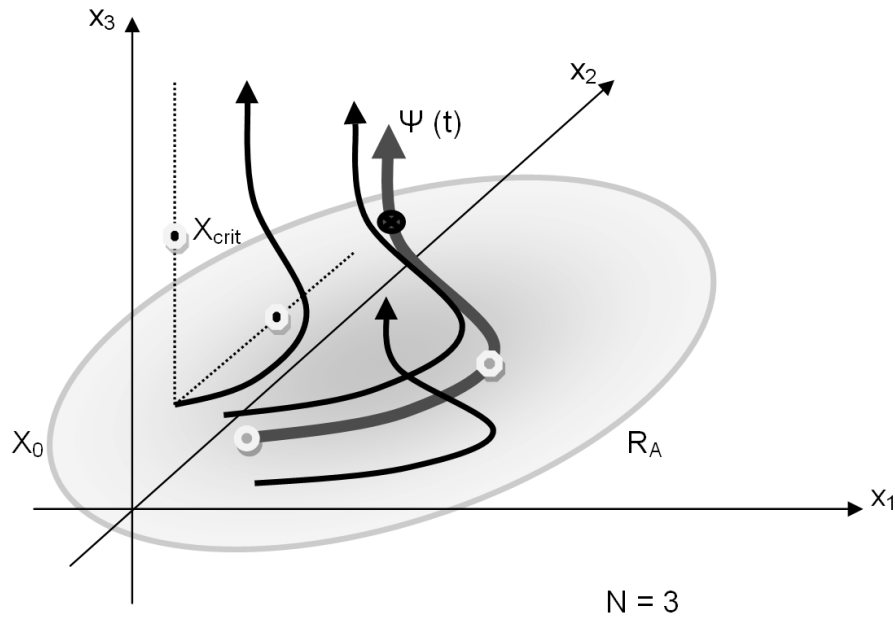


Fig.6.4 Example of predistored repair.

When dealing with complicated systems, system alliances and whole networks of alliances, there exist often numerous and unfortunately fuzzy criterions to determine if in a certain situation a particular object is suitable for use or not. It may happen that from a certain perspective it can still operate well, nevertheless, from another one its use has to be stopped already. The real decision can be therefore considerably problematic. Prolongation of the operation time, even though from a certain perspective the life-time is exhausted, can save some money, but because the general system degeneration cannot be stopped, it can happen that later the price of the necessary so-called general restoration will be much higher.

The choice of the optimal restoration strategy must, therefore, be done in every case very carefully.

The methods are, however, considerably effective and are also widely used, though they are still far from being complete. This is true first of all for considerably low-dimensional series prediction. If more system parameter time dependences have to be considered, one has to be very careful in any prediction diagnostics of eventual correlations among individual system parameter dependences.

7. Conclusion

Methods of prediction diagnostics have to be considered in general as a very sophisticated and effective tool for improvement of operation reliability (and in a certain respect also of safety, because high reliability is a necessary, but not sufficient condition for adequate operation safety) of the system, system alliance or eventually whole network of system alliances. Though these methods and necessary theory have been developed for about 20 years, our knowledge in this respect is still quite far from being complete.

This concerns especially cases of systems with a large number N of system parameters, systems with uncertain, fuzzy and contradictive properties and systems with strong correlation among their parameter dependences on independent variables. Also, the numerical effectivity of the prediction diagnostic procedures still needs improvement, especially in the cases of high N . The improvement of our knowledge in these areas is a challenge.

As we have mentioned, prediction diagnostics is useful not only for system operation failures prevention, but also for its risk and hazards decreasing, and, once a failure appears, for optimization of necessary repair procedures. In this field, a lot of problems are open not only in the restoration methods development, but also in their application. Without regard for the overall effort, the effectivity and level of sophistication of restoration procedures is very often considerably low because they are provided with very little knowledge of their possible optimization. The general level of losses caused by less sophisticated failed system repairs and restoration are tremendously high.

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