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LINKING OF FUNCTION CARRIERS WITH PHYSICAL CONTRADICTIONS

Milosav OGNJANOVIC (1), Jasmina BABIC (2), Sanja VASIN (1)
1: University of Belgrade, Serbia; 2: Military Technical Institute, Serbia

ABSTRACT

The current trend in the new product development is horizontal integration of various fields of technical solutions and principles of action (mechanical, electrical, software, etc). In order to provide integrated (multidisciplinary) products of higher quality level or to enrich the existing technical systems with electronic control or with artificial intelligence, the design structure should involve function carriers with various physical and other principles. Linking of function carriers with principles of action in conflict (physical contradictions) presents an important problem. The article contains the analysis of contradictory principles of action and identification of the ten groups of function carriers with contradictory principles. The cases study of existing technical solutions, support the basic hypothesis for established CFL methodology for linking solutions development. The methodology is based on the TRIZ and WOIS integration and a corresponding software application. For the new principle solutions search the application of bionic (biomimetic) approach is proposed. The integration and the new linking solutions development is based on cognitive decision making.

Keywords: design methodology, functional modelling, integrated product development, mechatronics, TRIZ

Contact:
Prof. Dr. Ing. Milosav Ognjanovic
University of Belgrade
Faculty of Mechanical Engineering
Belgrade
11120
Serbia
milosav.ognjanovic@gmail.com

1 INTRODUCTION

In the area of new product development, one of the current approaches is horizontal integration of various principle fields of technical solutions (mechanical, electronic, software, etc), so as to provide multidisciplinary products of higher quality level (Liu & Boyle, 2009) (Birkhofer-editor et al., 2011). Instead of looking for the new principle solutions, current integrated approach is to enrich the existing products with electronic control or with artificial intelligence and increase the quality of action (Choi et al., 2008) (Lindemann et al., 2009). Some of the reasons for this are explained in (Ognjanovic, 2011). The transformation of the existing technical systems with predominantly mechanical principles requires the rearrangement of the function structure and identification of the new relationships in this structure, the relationships between structure and product behavior, and the relationships between product and product environment. The new function carriers involved in the existing design structure are based on different (contradictory) principles, and the problem of linking becomes more complex and needs specific approaches to solution search. The main objective of this work is to create the methodology for linking of function carriers based on the principles of contradiction, i.e. those that are directly non-linkable.

Design methodology (Hubka & Eder, 1996) started with the function-based design (Pahl, Beitz et al., 2007) in the 1970s. Nowadays, the meaning of product function has been broadened and, besides technical meaning, economic, social, aesthetic, the emergence of other meanings gain in importance (Arisicchio et al., 2011). Also, the product features are brought in to be closely related with the product function (Gabelloni et al., 2011) and product properties (Krehmer et al., 2011). Function carriers also present the form of knowledge representation (Gu et al., 2012), and function carriers linking can be a very complex problem that requires complex research using various specific approaches, software tools, etc, for example statistical approach (Pourmohadi & Gero, 2011), to be solved. This is why the methodology for linking of functional carriers has to integrate all mentioned as well as other aspects.

Search for methodology of function carriers linking with physical (principle) contradictions, presented in this work, is based on search of already developed function carriers for linking and on already developed (or idea for development) hybrid (multidisciplinary) technical systems. Actually, this is an attempt to develop the approach in similar way as developed the TRIZ methodology which was based on the existing patents analysis. The result of this search, presented at the end of article, contains the TRIZ methodology application (Roof, 2006), (Rovida et al., 2009), (Hsieh & Chen, 2010), (Deimel, 2011), together with the WOIS principles, using the results of previously developed hybrid technical systems and new solutions which can provide the results of Biomimetics (Lean, 2009).

2 FUNCTIONS AND TYPES OF FUNCTION CARRIERS

The function of a technical system (TS) is the task or aim of the system. The function explains the system's effect and establishes a relationship between input (mode of conditions and mode of use) and output (behavior) of a technical system (Krehmer et al., 2011). Each goal can be translated into one or more functions that the product must carry out in order to fulfill that goal. In this sense, the functions are not separable from human perception: they are nothing else than the result of the user's interpretative process about the product's physical behaviors. Behavior is the way of physical and chemical state of the product evolving in time and in its environment. Behaviors express how the structure of the product reacts while carrying out specific operations. According to Aurisicchio et al. (2011), functions and systems' behavior have various effects such as technical, aesthetic, social, economic, and other (Crilly, 2010). In order to fulfill the TS goal and to increase its quality, various approaches to function structure modeling and structure of function carriers' creation are developed.

2.1 Function structure

According to Gu et al. (2012), two approaches of functional modeling are derived, one directly relates the function of artifacts to the structure of artifacts, i.e. F-S modeling; another one relates function of artifacts to the behaviour of artifacts and then to the structure of artifacts, i.e. FBS modeling. The first one, F-S, established by the Theory of technical systems (Hubka & Eder, 1996) (Pahl & Beitz, 1988) is oriented to creating the system structure in the form of organ structure. The main feature of these structures is that the structure of technical system functions and the structure of technical system organs are not directly related. One of the elementary functions can be carried out by a few organs and one organ can be involved in carrying out several elementary functions. Also, it is possible for one function structure to create a set of organ structures. Variation of organs or complete function carriers creates various contradictory effects.

The second approach, the FBS approach (Vermaas & Dorst, 2007), established by Gero (Gero & Kannengiesser, 2004) (Pourmohamadi & Gero, 2011), is oriented to improving the technical system behavior and presents the comparison process between actual behaviors of the structure, and expected behavior for function performance is proposed for design evaluation. In order to improve the TS's behavior and increase its quality of functioning, various secondary functions are involved in the functional structure and the organ structure. These secondary functions, including some main functions, can be carried out using all principles, mechanical, electronic or software. Electronic and software function carriers are more flexible and often with a higher level of efficiency (Wu at al., 2009). This has led to intensive development of mechatronic and other hybrid (multidisciplinary) TS’s, and to the development of Horizontal integrated methodology for product development. Numerous TS’s with existing principles of action are redesigned, i.e. transformed into mechatronic or into TS’s with artificial intelligence. In this sense, the structure of TS’s involves function carriers with various physical or other principles. Linking these function carriers with a different (opposite) principle of action had to be solved using additional secondary functions and carriers for the purpose.

2.2 Function carriers structure

The design process contains the transformation of function structure F into organ structure S, and then the identification of TS behavior B. Functional Behavior Transformation FAB (Function-Physical action-Behavior) (Chen et al., 2011) implies a systematic procedure identified by the linear and V-design model. Carriers are identified or developed for each particular function. In the function carrier development, the first step is mathematical description of the transformation process consisting of a function task. Then, there follows the identification of technical solutions based on some kind of mechanical principles capable of carrying out this transformation. Some of the mathematically described functions are more suitable or efficient to carry out by using electronic principle and some of them by applying a combination of electronic and software transformation. In the step of function carriers’ structure creation, a lot of function carriers are not “valent” to be involved in the TS structure. These are function carriers having a contradictory principle of action in relation to the others. Their valence ability has to be transformed and adapted so as to avoid linking contradictions.

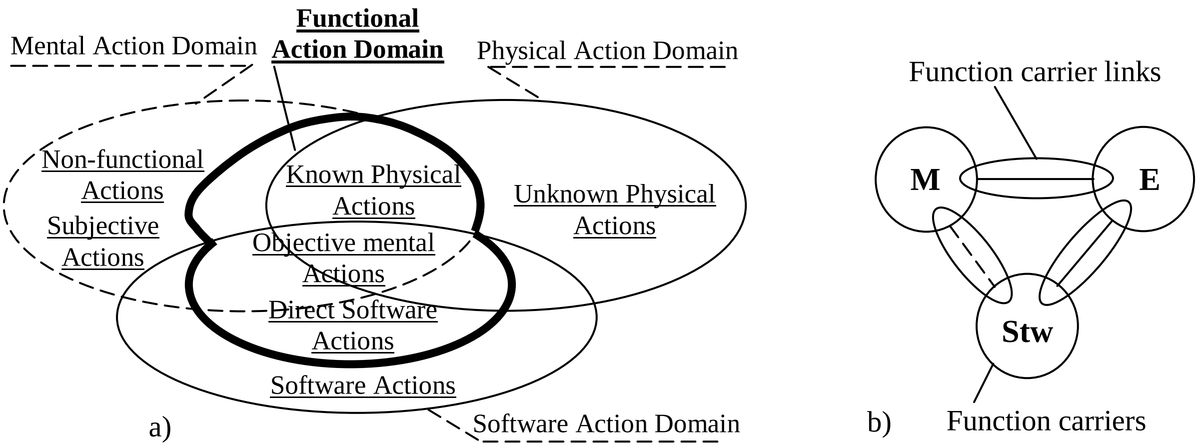

Figure 1. Linking contradiction of function carriers: a) function action domains relation, b) function carriers linking valence (M-mechanical, E-electronic, and Stw-software)

In Fig.1 the sources of linking contradictions and valence creation are presented. Function carriers act within some range of action domain, mechanical and electronic in the physical action domain, software functions in the software action domain and human functions in the range of mental action domain (Fig.1a). Human action can be objective (carrying out human functions) and subjective (decision making). Physical actions can be oriented to carrying out the TS functional structure (Known physical action) and to have other actions (Unknown physical actions). Applied software can act directly to carry out the TS functions and can be applicable to other actions. The TS functional action domain is the space of action, where the aim is fulfillment of all aspects, technical, aesthetic, social, economic and emergence, discussed by Arisicchio et al. (2011). In the space of action domain there can exist (act) function carriers with various physical and other principles. As a rule, these principles are not compatible (non-friendly) and it is not possible to link them directly in the TS structure. These contradictions are much more intensive between physical and software function carriers, or in relation with human function carriers than between function carriers with different physical principles. For the purpose of function carriers linking with contradictory principles of action, the secondary functions in the function structure have to be added to create the corresponding valences (links). For example, as presented in Fig.1b, to link mechanical and electronic (M-E), software and electronic (Stw-E) function carriers, various solutions for this linking are developed. In the above analysis, the developed solutions are used to create a general procedure for the purpose of linking valence creation (Fig.5).

3 CONTRADICTORY FUNCTION CARRIERS AND LINKING

Nowadays, technical systems are less and less mechanical. The other physical principles, such as electronic, software, even biological are more and more involved in technical solutions. Basically, TS's with the existing or new principles increase the level of quality, level of efficiency, and they get smart and are with artificial intelligence. Linking various mentioned principles in the same and compact technical solution presents a serious challenge to creativity in the engineering design process. Designers' knowledge and skills and methodology too have to be improved for solving these tasks. The cost of linking solutions has to be reduced using the existing or improved components. Also, the developed linking solutions present a guideline to the establishment of methodology for developing the new ones.

3.1 Solutions of function carriers in physical contradictions linking

In the past, the problem of function carriers linking with different physical principles was solved using empirical methodology and knowledge. Today, based on developed principles of linking, it is possible to carry out a review and analysis of principles and solutions for this purpose. As a result of this research, Table 1 shows ten groups of possible contradictory principles of function carriers that need to be linked in technical solution structures. Contradictory principles can't be linked directly and solutions for this purpose were gradually developed (from one to another TS generation) or directly. Representatives of these various solutions are presented in Fig. 2.

Table 1. The ten groups of contradictory function carriers

Types of function carriers with principles in contradictions			Type of linking solutions
1	Mechanical	Mechanical	Adapters/Connectors
2	Mechanical	Electronic	Sensors
3	Electronic	Mechanical	Actuators
4	Electronic	Software	A/D convertors
5	Software	Mechanical	Digital actuators
6	Mechanical	Hydro / Pneumatic	Pumps/compressors
7	Hydro / Pneumatic	Electronic	Sensors
8	Human	Mechanical	Human action
9	Human	Electronic	Control panel
10	Human	Software	Computer

In the relationship and linking of function carriers with mechanical principles (group 1 in Table 1), physical contradictions can arise if these principles are not the same, or if direct linking is not possible. Usually, it is possible to say that these carriers do not accept each other and in morphological matrix stay out of linking. However, the solution for linking can be the result of additional secondary functions and function carriers that solve this contradiction. These are various kinds of adapters or connectors. Fig. 2 shows a representative of this group of secondary function carriers. This is synchronic coupling which makes possible alternative connection of various gears with the same shaft in an automotive gearbox. Furthermore, physical contradictions are common if the function carriers, which should be linked, have a different physical operating principle. As mechatronic systems are a combination of mechanical and electronic components (function carriers), linking presents the main task in those systems design. The relationship between mechanical and electronic function carriers

principles (group 2 in Tab.1), and vice versa (group 3), was a challenge for special design and production of separate components for this purpose. This is a group of various sensors which transforms mechanical actions of function carriers with mechanical principles into electric charge, voltage or current that can be used for electronic components (function carriers) action. Also, electric physical values in connection with mechanical components have to be transformed into mechanical values such as force, motion etc. Various kinds of actuators (the group 3) are developed for the purpose. The range of sensors and actuator families is broad. The reason is that the number of physical values that have to be transformed is large and the range of these values variation is large too. For the purpose of manufacturing transducers (group 2) and actuators (group 3), a specialized area of product development and industrial production is arranged.
In the past, in technical systems development, mechanical principles gradually gave way to electronic principles, and electronic systems were gradually transformed into software (information) systems. Software function carriers had to be linked to electronic function carriers (group 4 in Tab.1) and to mechanical ones (group 5). The linking problem distinguishing electronic and software systems is a different type of signals that define physical values. Electronic signals can be analogue and digital. Since software systems are digital, analogue values have to be transformed into digital, and vice versa. This secondary function of the signal transformation is carried out by an analogue-digital (A/D) converter (4 in Fig. 2). In the case with digital electronic function carriers this transformation is unnecessary. For example, in digital motors used in robotic systems for different kinds of motion, the control process is carried out directly by software digital signals. These solutions present a direct link between software and mechanical function carriers (group 5 in Tab. 1 and Fig. 2). Function carriers with hydro and pneumatic physical principles are also in physical contradictions and linking with mechanical or electronic function carriers is the result of secondary functions and function carriers for this purpose. Fluid pressure has to be provided by high-pressure pumps and compressors (group 6 in Tab.1 and Fig. 2). Fluid pressure control in the pumps-compressors and hydro or pneumatic actuators is carried out by fluid sensors (group 7).

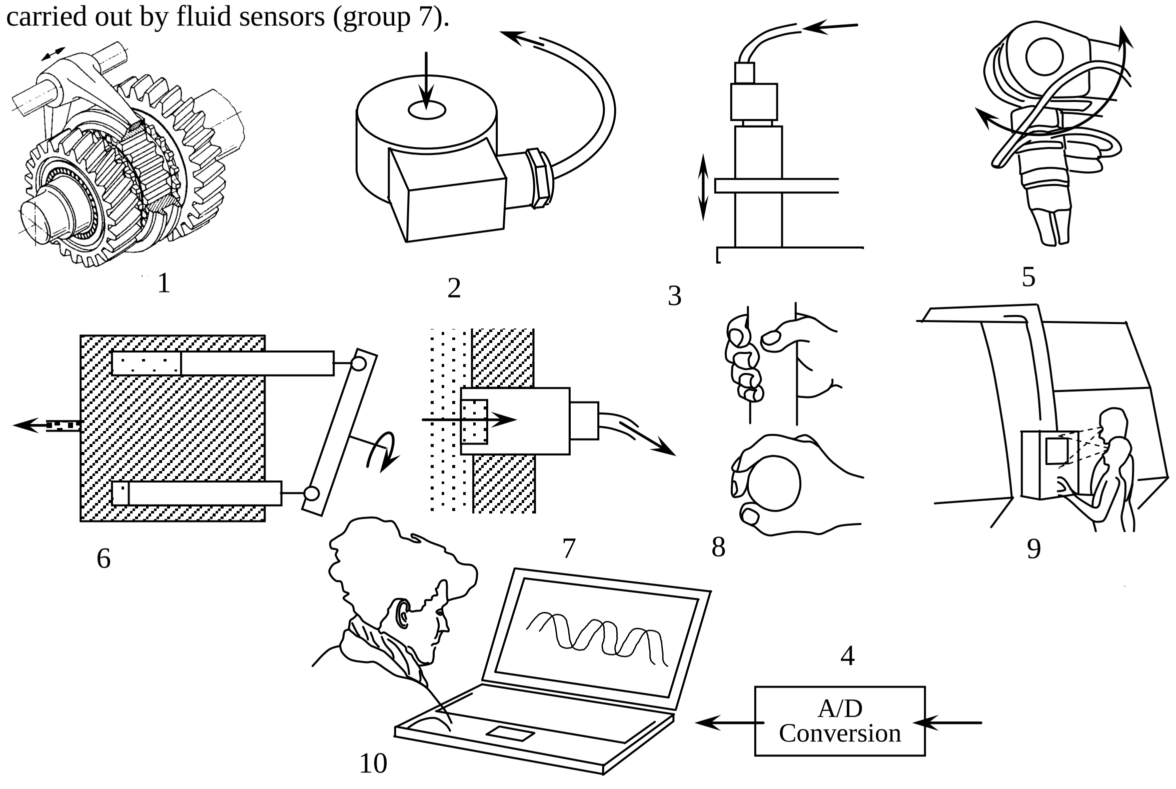

Figure 2. Representatives of secondary function carriers' solutions for linking of function carriers in physical contradictions

Human action (carrying out some of the functions) also has to be linked with mechanical, electronic or software function carriers. Human action is, as a rule, cognitive and it is the result of information processing and decision making according to the results of technical process monitoring. Cognitive decisions are transformed into mechanical human actions by hands or legs. These actions also have to be transformed at initialization of mechanical or electronic and software action of corresponding function carriers. Mechanical action at the control bars of steering mechanisms presents mechanical linking of mechanical function carriers with human action (group 8 in Tab.1 and Fig. 2). Human communication with electric or electronic function carriers is provided by control panels and corresponding buttons or similar control devices (group 9 in Tab.1 and Fig. 2). Interactive communication with a software system linked to electronic or mechanical function carriers is carried out using a computer with the corresponding software (group 10 in Tab.1 and Fig. 2). The trend in the new technical systems development is the replacement of electronic function carriers (analogue and digital) by software systems that operate using artificial intelligence or interactive correspondence with human (user).

3.2 The cases study of contradictory function carriers linking

The objective of these cases study is to identify the process of a certain design solution quality level increase by the application of function carriers with the contradictory physical principles and the process of contradiction solving. Furthermore, the objective is to identify the challenges and the future trends in this course by using previously developed and existing solutions, including the methodology of problem solving.

As explained above, the contradictory physical principles of function carriers exist in technical systems that consist of all mechanical function carriers. Fig. 3a displays a differential gear unit which is applied in mobile machines (passenger cars and other). The function of this unit is to provide different rotation speeds of wheels in curvature motion. The disadvantage of the classic solution of these function carriers is disappearing of the traction torque at both wheels when one of them starts to slip. The new solution presented in Fig. 3a contains two friction couplings which blocked free rotation of one wheel relative to another. In the course of curvature motion it is necessary to increase the pressure at the coupling near the wheel that has to slow down and reduce the pressure at the coupling near the wheel that has to increase speed of rotation and enable coupling slipping. When it is necessary to increase and reduce pressure force at the same time, this is physical contradiction. The solution is found using the mechanical principle. The force adapter is based on inclined planes with difference in angles for the left and right side. The difference in angles is opposite for opposite direction of relative motion between the wheels. Higher angle produces higher force, and vice versa. This adapter together with the friction couplings makes possible to have traction torque at both wheels proportional to the pressure at the friction coupling and at the same time wheel rotation with different speeds.

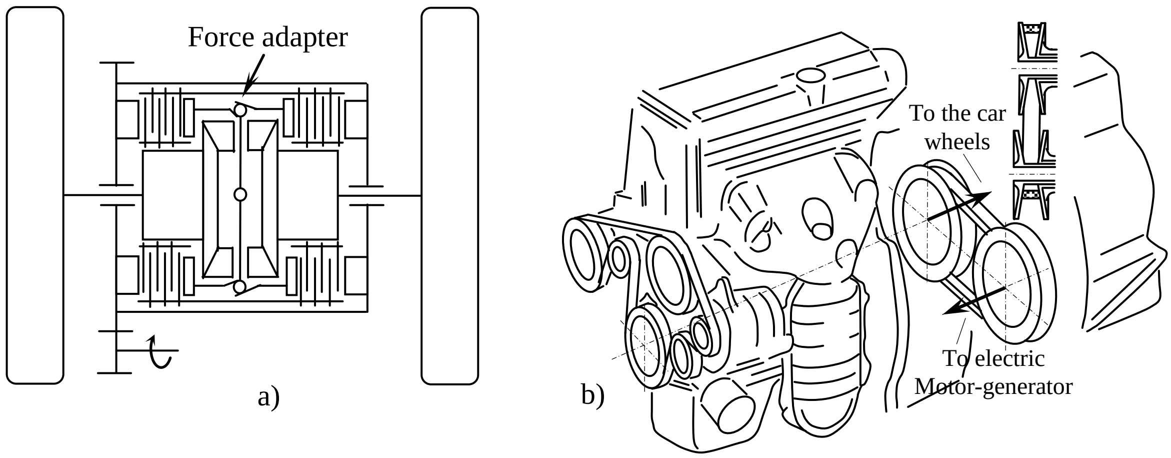

Figure 3. Examples of mechanical function carriers linking with physical contradictions: a) using force adapter in automotive gear differential unit, b) using CVT in hybrid passenger car traction unit

Hybrid passenger cars are powered by a combination of internal combustion engine and electric motor-generator. In the combination of these power sources, excess of mechanical power is transformed into electric charge of batteries. The car traction provides electric motor and the function of engine is to help electric drive or battery charging. The functions of engine and motor are in multiple physical contradictions. Both of them are the sources of mechanical power, but the direction of this power transmission frequently changes. Furthermore, speed and level of the necessary torque varies. Linking of these two components was a very complex task. Research in this direction resulted in the development of Continually Varying Transmission (CVT) unit. This adapter is based on the mechanical principle similar to the friction (belt) variation (Fig. 3b). Control of CVT transmission ratio and change of power flow direction, is performed using electronic subsystems. The CVT in itself is a complex mechatronic system, whose main function is to link the engine and motor-generator in the traction unit applied in passenger cars.

The wind turbines are not really a new technical solution. The wind power is transformed by the propeller into a slow rotation with the high torque. The task of the gearbox is to transform (increase) the speed of rotation to the level sufficient for current production in an electric generator. The speed of rotation is closely related to the wind speed and electric power produced by electric generator does not correspond to a common electric net. The transformation of electric power parameters is a complex process and significantly reduces the efficiency of wind plants. The new idea is to provide a link between wind turbine and electric generator to produce electric power with parameters ready to be directly synchronized in the common electric net. The unit which can provide this adaptation consists of one additional planetary gear set (Fig. 4) with the outer toothed ring which is not fixed, and also free for rotation (Hohn, 2012). The rotation of this toothed ring is controlled by electric motor-generator. If the wind speed is slow, the gear ring rotation increases the transmission ratio and in the case when the wind speed is high, the motor will act as an electric break and will decrease the gear unit transmission ratio. The speed of electric generator has to be maintained at the same level. Electronic controller provides this condition. Motor-generator varies the speed of rotation according to the Controller signal, and consumes or produces electric power. The main electric generator with permanent and constant speed of rotation is synchronized directly at the electric net. Gearbox and electric generator are linked using a complex mechatronic system combined of the generator speed sensor, controller, speed actuator and motor-generator.

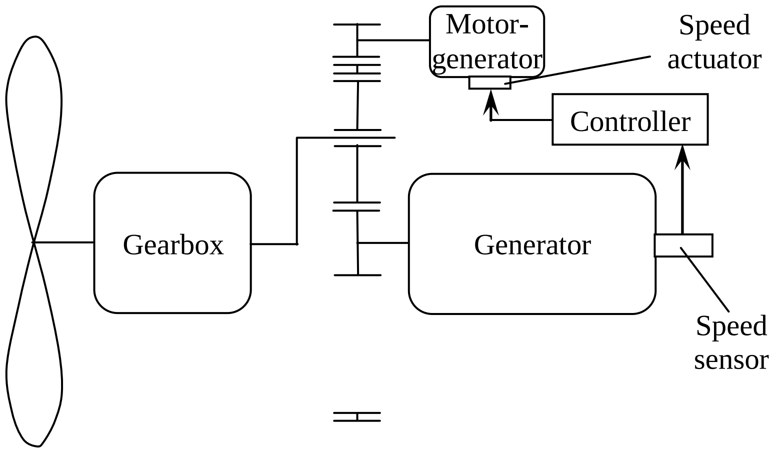

Figure 4. Linking of gearbox and electric generator in the wind turbine synchronized in the electric net

All the three cases (examples) show as follows. Linking of the main functions carriers with physical contradictions requires complex hybrid technical solutions (Fig. 1b). Secondary functions, for this linking, present a complex structure and play an important role in the system operation. The objective of this presentation is to identify those principles in the existing solutions, and to establish the procedure and methodology for efficient solving of these problems at first attempt.

4 PROCEDURE OF CONTRADICTORY FUNCTION CARRIERS LINKING

The two approaches to solving contradictory problems are available, using the TRIZ and the WOIS methodology. These methods also have contrary approaches in creating the design solution. Althsuller (Hsieh & Chen, 2010) created 40 TRIZ inventive principles and 39 engineering features, which resulted from the existing patents analysis. Using the TRIZ principles, the solution to a contradictory problem solving is developed by searching for a compromise between contradictions (Li, 2010). The WOIS principle solves a contradictory problem without a compromise, depending on paradox necessity and in the direction that is more important. The WOIS approach is more common in creating patent solutions. The patent inventor has the target and is looking for a solution that is more ideal in paradox requirements fulfillment without a compromise between contradictions. Since the TRIZ methodology is formed on the basis of patents, then the TRIZ and the WOIS can be coupled by the same token via inventive principles and engineering features established by patent analysis. In this case, solutions in terms of function carriers with contradictory principles linking (Table 1 and Figure 2) were developed mainly by a methodology that would meet the WOIS approach. These solutions represent some kind of patents. If these 10 groups have been already taken as a basis of the existing linking solutions, analogous to 40 TRIZ principles, it is possible to define integrated WOIS and TRIZ methodology oriented to searching for the new solutions for the purpose of function carriers linking with contradictory principles. This means that the solutions developed so far by the WOIS methodology, create directions in looking for the new solutions, using the TRIZ methodology. These evolutionary searches have the task to find out the new or more efficient solutions to linking of function carriers with contradictions in action principles. Fig. 5 shows this integrated procedure that is based on: (a) identification of contradictions and properties of function carriers which have to be linked, (b) integration of TRIZ and WOIS methodologies based on existing linking solution and the new one produced by Biomimetic methodology, and (c) interactive decision making in iterative convergence to linking solution. These three aspects create the proposed methodology and present guidelines for further research in this area.

4.1 Physical contradictions identification

According to Altshuller (Orloff, 2004), physical contradictions present conflicts of physical properties in the space domain, time domain, structure domain and material domain. Functions and function carriers presented in Table 1 contain all of them and even more. On the other hand, these principles have to be in operating status at the same time and in the same space. Linking valence creation is based on identified function carriers' properties which need to be linked. In Fig 5 the two activities for this purpose are anticipated: identification of contradiction and then identification of the properties of function carriers which need linking. The procedure has the next steps. The first one arises from the inability to connect the two function carriers in TS organ structure. Identification of contradiction means to find out the difference in the principles of action, such as various kinds of physical principles (mechanical, electronic, magnetic, nuclear,…), chemical, biological, software and mental (human). The difference in the principles of function carriers' action can be inside of one of them, for example in two function carriers with two different mechanical principles of action or different electronic principles, etc. A higher level of principle differences is found between mentioned groups, such as mechanical or software, or biological and others. The next step is the properties identification of both function carriers that should be connected. For example, among electronic components this is current, voltage, charge, for mechanical components these are velocity, displacement, force, etc. The value of identified properties determination is the last step in the procedure of contradiction identification.

4.2 The TRIZ and WOIS methodology integration

Searching for methodology of function carriers linking with incompatible properties is performed applying the analogy of TRIZ development. This method was developed based on the analysis of patent solutions. In this case, the base is created by ten groups of solutions for function carriers (FC) linking presented in Tab.1 and Fig. 2. The contradictions and properties identified in previous activity correspond to one of these groups. For every group, the proposed procedure for further activities is found in the base of contradiction type entities (Fig.5). The base contains entities for contradictions already recognized. When the new contradiction appears, a new entity is possible to add in the base. The identified properties of FC are the output and input of FC in conflict which have to be linked. Linking needs first their mathematical presentation (modeling) of these properties transformation. Then follow the search for a carrier capable of carrying out this transformation. This search is an iterative process that consists of attempts to establish FC link with the existing linking components and the development of new. Step by step the search process converges to a definitive solution. In this process, the application of I-TRIZ software (Ideation International Inc.) is suitable. This application firstly contains preliminary analysis using a corresponding questionnaire and then formulation of the problem using the Problem formulator. The choice of direction for problem solving is the action, which has to be done before the concept solution is suggested. In order to provide the cost-effective solution it is necessary to attempt to apply the existing components such as presented in Fig.2. If in some cases there is no convergence or if convergence leads to expensive solutions, the user of methodology can apply the WOIS method to find the solution that will satisfy the contradictions, including cost, without a compromise. This is the action undertaken by the methodology user, which forms an integrated approach by combining the TRIZ and WOIS methods. This integrated methodology for contradictory function carriers linking – CFL includes the procedures based on the existing solutions for linking and search for possible new ideas and principles that will be in the future predominantly based on the principles taken from biological systems – Biomimetics (Lenau, 2009).

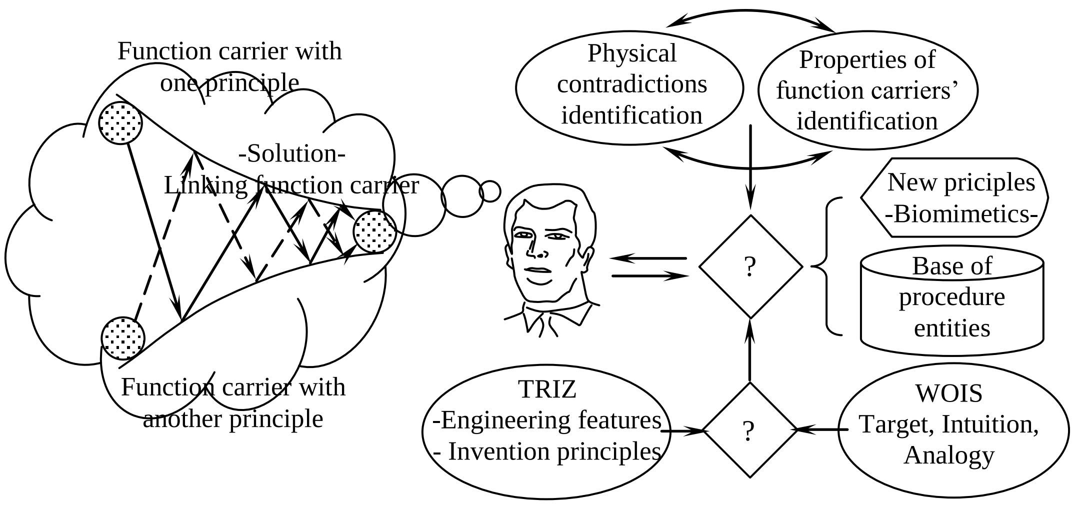

Figure 5. Contradictory function carriers linking – CFL methodology

4.3 Interactive decision making

The dominant role in CFL methodology is cognitive decision making, made by methodology user. The TRIZ methodology is guiding the process but can't replace the designer. The I-TRIZ software makes combinations and relations, and supports decisions. The background for decision making can be cognitive thinking, intuition, or application of some methods for decision making such as optimization, genetic algorithms, fuzzy logic, neural nets etc. Cognitive thinking provides: (a) convergence to definitive solution (Fig.5), (b) choice of the procedure entity for creating a solution, (c) guidance for the process of linking solution creation and choice of the TRIZ or WOIS method, (d) choice among the existing linking components in order to reduce cost, (e) proposal or creation of new biomimetic solutions in order to enhance the existing solutions, and (f) making definitive decision about linking solution. A designer or designers' team carries out a complex network of interactive decision making according to CFL methodology. Involved methods and tools only support decision making.

5 CONCLUSION

The aim of presented procedure is to contribute to general and current trends for increasing the quality level of the new or existing technical systems. A new generation of technical systems is predominantly based on the existing principles but enriched with electronic and software control (intelligent, multidisciplinary, integrated systems). Function carriers are in strong principle contradictions and their linking opens up a special field of interest. The article contains the following results.

- Correlation of the action of function carriers with principles in conflict.
- The ten groups of contradictory principles are identified.
- Linking of function carriers with physical contradictions is supported by existing examples.
- The cases of integrated multidisciplinary TS and linking of function carriers are presented.
- The CFL methodology for contradictory function carriers linking is established. The methodology contains identification of contradictions and integrated approach to the TRIZ and WOIS methodology application, including the new linking components development based on biomimetic approach.

The direction of this approach should encourage the development of technical systems closer to biological ones, where function carriers are harmonized with various physical and biological principles.

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