Ertek, G., Erdogan, A., Patoglu, V., Tunç, M.M., Citak, C., Vanli, T., 2012, 'Encapsulating And Representing The Knowledge On The Evolution Of An Engineering System', Asme Idetc/Cie 2012. August 12-15, Chicago, Il, Usa.

Note: This is the final draft version of this paper. Please cite this paper (or this final draft) as above. You can download this final draft from http://research.sabanciuniv.edu.

ENCAPSULATING AND REPRESENTING THE KNOWLEDGE ON THE EVOLUTION OF AN ENGINEERING SYSTEM

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ABSTRACT

This paper proposes a cross-disciplinary methodology for a fundamental question in product development: How can the innovation patterns during the evolution of an engineering system (ES) be encapsulated, so that it can later be mined through data analysis methods? Reverse engineering answers the question of which components a developed engineering system consists of, and how the components interact to make the working product. TRIZ answers the question of which problem-solving principles can be, or have been employed in developing that system, in comparison to its earlier versions, or with respect to similar systems. While these two methodologies have been very popular, to the best of our knowledge, there does not yet exist a methodology that reverse-engineers, encapsulates and represents the information regarding the application of TRIZ through the complete product development process. This paper suggests such a methodology that consists of mathematical formalism, graph visualization, and database representation. The proposed approach is demonstrated by analyzing the design and development process for a prototype wrist-rehabilitation robot and representing the process as a graph that consists of TRIZ principles.

INTRODUCTION

TRIZ is a methodology for inventive problem solving, and has been used extensively in product design. TRIZ was formally introduced byAltschuller in 1940s, based onobservations of more than 200,000 patents [1]. Altschullerrecognized that a vast majority of patents involved incremental improvements on earlier inventions, rather than presenting radical novelties [2]. Furthermore, these improvements were based majorly on a given set of general principles to solve the contradictions among a set of conflicting features. Altschuller identified 39 such features and 40 such principles, which are listed and described in Appendices A&Bof the supplement to this paper [3]. TRIZ theory is based on three primary postulates [4]:

1) There exist objective laws that drive the evolution of engineering systems,

2) The evolution of an engineering system is a sequence of contradictions and their resolutions (Laws of Engineering Systems Evolution, LESE),

3) The peculiarities of a given situation should be taken into consideration during the problem-solving process.

The focus of this paper is the encapsulation of the knowledge pertaining to LESE, the second postulate of TRIZ. The milestones of the design process can be recorded in terms of the TRIZ principles applied during the process itself, or can be reverse-engineered at the end of the process. The goal is to guide the design process better in similar future projects, based on the path followed in earlier projects, and based on insights obtained from the analysis of process visualizations. Another important application of the proposed methodology is the analysis of evolution patterns of a particular family of finished products in the market through patent analysis [5]. To the best of our knowledge, there does not exist a formal framework that enables the encapsulation of this evolution pattern data.

The research question in this paper is the following: *How can the innovation patterns during the evolution of an engineering system (ES) be encapsulated, so that it can later be mined through data mining methods?*

The effective capturing of design process knowledge can help greatly in understanding the design rationale, which is the explanation of why a product, or some part of a product, is designed the way it is [6]. Furthermore, this knowledge can also contribute to future product design cycles: 90% of industrial design activity is based on variant design [7]. During a redesign activity up to 70% of the information is taken from previous solutions [8]. Hence, effectively capturing and reusing product design knowledge can enhance or impede greatly the achievement of a robust knowledge management system for product development [9]. The paper contributes to the literature primarily by proposing a knowledge encapsulation and representation method that includes mathematical formalism, graph visualization, and database representation. The information gathering can be during or after the design process. Furthermore, the developed knowledge representation methodology is demonstrated using a case study of a wrist rehabilitation robot. This is an important domain of application, due to the increasing importance of rehabilitation robots in the health sector, and due to the increasing costs in the health sector. In the case study application, the TRIZ contradictions and principles encountered during a wrist rehabilitation robot design are revealed,

serving as a reference for the design of similar robots.

LITERATURE

Rehabilitation Robotics

Physical rehabilitation involves exercising and manipulating the body to improve joint and muscle function [10], and has traditionally been performed by human therapists, who help and direct patients with repetitive physical movements.

The costs of health care services are at a steady increase throughout the world. For example, the cost of medical services alone in US jumped from $961 billion in 2000 to $1,584 trillion in 2007 [11], showing a 65% increase in those seven years. The demand for and the cost of physical therapy is increasing as a part of the increased demand for health services. As of 2009, 1,275,000 people in the United States were living with spinal cord injury alone, requiring physical therapy on hands, limbs and/or other parts of the body [12]. In 2007, the $600 million share of the US health expenditures consisted of the aggregate pay to therapists. While the health expenditures are increasing, the number of therapists in the US stayed the same from 2006 to 2007, and the yearly wage of a therapist has increased by nearly $8000 [13]. Physical therapists are the second highest paid among all human therapists, following radiation therapists [14].

Rehabilitation robots can be extremely useful in the treatment of rehabilitation patients (Appendix C in the supplement [3]), and hence the design of the robots is significant for the treatment. Critical design criteria for rehabilitation robot design are safety and ergonomy. The designed device should enable safe and versatile training while patients are attached to the robot, and the robot should be compatible with the natural movements of the user. Further constraints on design include light and compact mechanism with a simple user interface and possible artificial intelligence capabilities [15]. Design requirements for rehabilitation robots can be collected through interviews and surveys, and the appropriate analysis of such feedback can provide major insights for the design process [16]. Technical and nontechnical limitations of available robot systems pertain to the inability of robots to sense, complete safety of the patients, user centered design, and cost and usability [17].

In the literature, several robotic devices have been developed to target wrist rehabilitation exercises, and these are reviewed in Appendix D of the supplement [3].

TRIZ

TRIZ technique is a systematic problem solving methodology invented by Russian scientist GenrichAltshuller, to bring creative solutions to challenging design problems [2]. The acronym TRIZ stands for "Theory of Inventive Problems Solving" in Russian.

Before the invention of the TRIZ, Altshuller worked on over 200,000 patents with the feature of revealing general patterns of invention/innovation [1]. His research resulted in three fundamental findings:

1) Problems and solutions are not unique for industries and sciences.

2)Technical developments are repeated in industries and sciences.

3) Innovations are used outside of the original domain for which they were developed.

Thanks to these findings, Altschuller identified 39 design features, which may contradict with each other at different steps of the design process, and 40 principles of problem solving that can be applied to resolve these contradictions. The recipe for the appropriate set of principles that can be applied to solve each contradiction are provided in the contradiction matrix [18].

Many successful applications of TRIZ in the real world have been reported in literature, including the design of welding fixture [19] and trend analysis of formwork engineering technologies in the construction industry [20]. Some of these applications particularly involve rehabilitation and rehabilitation robots, and will be discussed next.

TRIZ for Rehabilitation

[21]designed and developed a robot for assisting eating, where they applied TRIZ. Specifically, the segmentation principle of TRIZ is mentioned as a major step of the design process. The researchers decoupled the robot's feeding actions, named as self-feeding actions, into two, picking the food and transferring the picked food to disabled person's mouth. Therefore, two separate robotic arms were designed on the robot for two different subsections, so the design was improved in terms of its usefulness, benefits, convenience and conformance to manufacturing. [22]applied TRIZ to improve aging in place, to live in one's own home as long and as comfortable as possible.

[23]describes a rehabilitation robot that assists with disability inspired by passive walk that requires no actuators, sensors or controllers that able to walk down slopes. Through TRIZ, the researchers overcame a contradiction through the "inversion" TRIZ principle. [24]also applied TRIZ principles to resolve contradictions in the design of a rehabilitation robot.

Evolution of an Engineering System

Our study builds upon an earlier idea by [25] and [26], who highlight the necessity to collect the information during the evolution of an engineering system, within the framework of Laws of Engineering Systems Evolution (LESE), the second postulate of TRIZ.

Systematic collection of data regarding the evolution of a design of a particular product or a product family can enable innovative insights. For example, [27] investigates the correlation between the step of evolution and the contradictions that characterize the behavior of an engineering system, through a case study on tablet manufacturing technologies. The ultimate goal in [27] is to determine the maturity stage in the lifecycle of the system.

Knowledge Representation

Knowledge representation can be defined as the application of logic and ontology to the task ofconstruction of computable models of some domain [28]. A knowledge representation (KR) for a domain should cover the information in the domain in depth and breadth, and should be consistent, so as to eliminate redundant or conflicting knowledge. A KR should also be easily understandable, efficient, and flexible. A KR formalism should ideally allow the representation of knowledge in an explicit and declarative way, should be logically founded, should allow for structured representation of knowledge, should have good computational properties, and should allow users to understand and control every step of the knowledge base building process [29]. [29]presents a thorough discussion of how knowledge can be represented through graphs, and our research also includes the representation of knowledge in graphs.

METHODOLOGY

Our proposed methodology for the encapsulation and representation of knowledge reflects the evolution of an engineering system (ES), and consists of mathematical formalism, graph visualization, and database representation.

Mathematical Formalism

We now present the mathematical formalism for representing the TRIZ goals, contradictions, and the TRIZ principles used to solve these contradictions.

Let:

i : evolution step (stage) between versions i and $i + 1$ of the product

j : evolution sub-step (sub-stage) within any step

k : a contradiction that occurs in a step/sub-step of the product design

g_{ijk}^+ : the TRIZ goal that needs to be improved at step (i, j), but is involved in contradiction k at this step/stage

g_{ijk}^- : the TRIZ goal that degrades as a part of contradiction k at step (i, j)

K_{ij} : set of contradictions encountered in sub-step j of step i

k_{ij}^* : the contradiction that is selected for resolution at sub-step j of step i

P_{ijk^*} : set of TRIZ principles that can be applied to resolve the selected contradiction k^*

$p_{ijk^*}^*$: the selected TRIZ principle to resolve the selected contradiction k^* at step (i, j)

Graph Visualization

We suggest that the process visualizations be graph visualizations, where nodes represent the possible contradiction-resolving TRIZ principles that can be applied in each design state, and the evolution path represents the principles actually selected and applied. The proposed graph visualization is very simple, and there can be other graph visualizations that can be developed in future research, based on the mathematical formalism. [30]is one of the rare studies that introduce visualization of data regarding the application of TRIZ. The authors introduce the concept of "contradiction clouds" for representing a set of contradictions that are encountered at any step of the evolution of an engineering system.

The graph visualization creates layers of nodes, where the layers represent steps and sub-steps of the evolution. The nodes on a layer represent the set of possible TRIZ principles that can be applied to resolve the contradiction at that (step, sub-step). The TRIZ principle selected at each (step, sub-step) is shaded with color, and the shaded nodes in successive layers are connected with arcs.

Figure 1 illustrates the graph visualization obtained for the design process in the case study. The methodology we propose successfully reverse-engineers the design process, and illustrates it in a graph, which succinctly shows how TRIZ was implicitly applied throughout the design process.

This graph representation has the following benefits:

1) The reverse-engineered design process is represented visually, which provides meta-information easily accessible.

2) The graph visualization yields immediate insights for the analyzed process; that may be difficult to read from textual descriptions. For example, Figure 1 clearly illustrates the recurring appearance of principles 34 and 35 in the last two steps of the process. Also, it shows that the path followed during the process used principle 34 twice in the last two steps of the design process. This shows the importance of TRIZ principle 34 ("rejecting and regenerating parts") in later steps or the product design process for this robot, and suggests that it may hold true for other similar rehabilitation robots.

3) The design processes followed in the development of a particular product, such as the AssistOn-wrist robot in the case study, can guide the development of similar products.
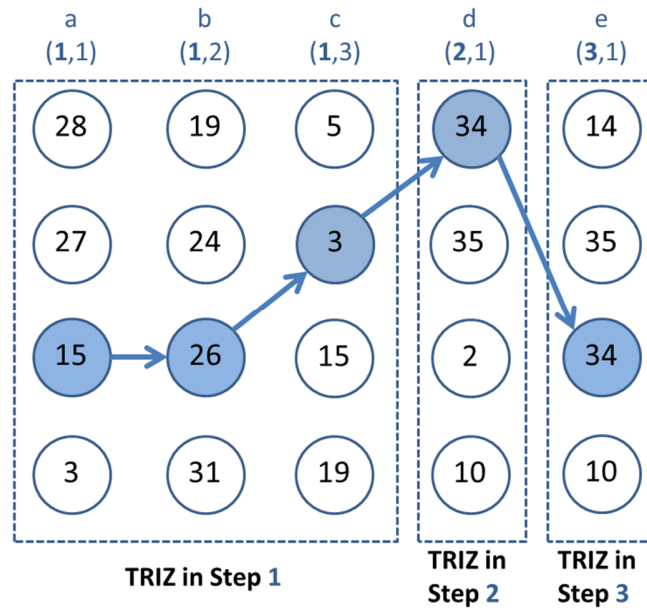
FIGURE 1. THE VISUALIZED DESIGN PROCESS, WHERE EACH NODE REPRESENTS A TRIZ PRINCIPLE AND THE SHADED NODES REPRESENT THE SELECTED PRINCIPLES.

TABLE 1. DATABASE STRUCTURE, CONTRADICTION TABLE

ID	i	j	k	gp	gp_detail	gm	gm_detail	is_k_selected
a	1	1	1	39	...	2	...	1
b	1	2	1	21	...	27	...	1
c	1	3	1	37	...	22	...	1
d	2	1	1	33	...	21	...	1
e	3	1	1	26	...	14	...	1

While the visualization is very simple, it does enable the convenient communication of the design process, and the derivation of key insights regarding the process. It is highly probable that similar products with similar design criteria will require a similar design process, even if the design itself may vary significantly. One future research could be the simultaneous analysis of multiple design processes, using graph-theoretic concepts, such as graph metrics for characterizing graphs [31][32].

TABLE 2.DATABASE STRUCTURE, TRIZ_PRINCIPLE TABLE

i	j	selected_k	p	is_p_selected	explanation
1	1	1	28	0	...
1	1	1	27	0	...
1	1	1	15	1	...
1	1	1	3	0	...
1	2	1	19	0	...
1	2	1	14	0	...
1	2	1	26	1	...
1	2	1	31	0	...
1	3	1	35	0	...
1	3	1	3	1	...
1	3	1	15	0	...
1	3	1	19	0	...
2	1	1	34	1	...
2	1	1	35	0	...
2	1	1	2	0	...
2	1	1	10	0	...
3	1	1	14	0	...
3	1	1	35	0	...
3	1	1	34	1	...
3	1	1	10	0	...

DatabaseRepresentation

In real world engineering projects, the encapsulated design process knowledge should be stored in a database, according to a structure, in the form of explicit information/data. We propose a database structure that directly reflects the mathematical formalism above, and consists of two database tables. The database tables CONTRADICTION and TRIZ_PRINCIPLE store information regarding the contradictions and the TRIZ principles that can and have been used to solve those contradictions. These tables, populated with the information collected during the case study, are given in Tables 1 and 2.

In implementations, any relational database (MS Access, MySQL) can be used to encapsulate and store the extracted design process knowledge the established tabular data structure enables the adoption of standard data analysis/mining techniques that operate on tabular data.

CASE STUDY

AsistOn-Wrist

AssistOn-Wrist (Figure 5) [33][34] is an exoskeleton device for rehabilitation and training, and is designed as an enhanced version of the RiceWrist[35] (Figure 2).

The mechanism is of hybrid kinematic structure and comprises of a 3RPS parallel wrist in series with an actuated revolute (R) joint at the base platform of the wrist. It consists of five bodies: a base platform F, three extensible links R, S, T, and a moving platform W. The end-effector held by the operator is rigidly attached to the moving platform W. Extensible links are connected to the base platform via revolute joints whose axes of rotation are oriented along the tangents of F, while the moving platform is connected to the extensible links by means of spherical joints. Translation degree of freedom of the device is used for ease of attachment and configuring the device for each patient. Remaining three rotational degrees of freedom are to apply therapeutic exercises for forearm supination/pronation, wrist flexion/extension and wrist radial/ulnar deviation.

All of the devices mentioned in the literature (Appendix D, [3])are implemented using serial kinematic structures, since serial robots are advantageous while targeting for a large workspace, as demanded by rehabilitation applications. However, with these kinds of mechanisms, it is hard to

ensure good alignment of the robot axes with human joint axes, another imperative design requirement for rehabilitation robots. When serial mechanisms are employed, this ergonomic requirement necessitates use of adjustable linkages and straps, and manual adjustment of these link lengths may result in cumbersome installation and calibration processes. To this end, parallel mechanism based exoskeletons, such as AssistOn-Wrist, excel as feasible alternatives, since the alignment of the rotation axes of these devices with the human joints can be ensured through kinematic design and/or active control of such devices. Moreover, mechanisms with closed kinematic chains result in better actuator utilization, and inherently possess compact designs with high stiffness and low effective inertia, making it easier for them to satisfy the transparency requirement of force feedback applications. These mechanisms are also advantageous as measurement devices as they do not superimpose positioning errors.

AssistOn-Wrist makes use of these advantages with an exoskeleton parallel wrist structure and it has the ability to measure the joint angles and give kinesthetic feedback to human wrist with high precision. Through optimization, range of motion and manipulability of the device is enhanced with a singularity-free workspace. Furthermore, dynamic performance of the device is increased in the design step so that it is back-drivable with minimal joint frictions and backlash. Therefore, negative effects of the dynamics are kept minimal and in result it is made possible to implement correct rendering of the virtual environments without additional force sensor integration [36]. Thanks to passive back-drivability, in the case of an electrical failure, patients can easily move their arms to a safe and comfortable configuration and detach themselves from the robot, while open ring kinematic structure along with an asymmetric joint placement enables rapid attachment/detachment.

Device has gone through several design iterations, starting with the first prototype, RiceWrist, implemented at Rice University. Afterwards, second prototype was designed and implemented at Sabanci University in one and a half years, where design process itself took approximately six months. This version possesses major design upgrades with respect to the first prototype. Further design modifications were carried out in the third version, motivated by the feedback acquired from the therapists and it was designed and implemented in another year, where this time the design process was carried out in four months. Fourth version has slight modifications in design while emphasis is shifted on the controller implementations, which took approximately one year to finalize. A fifth version is planned to be implemented in one year, which would inherit design modifications motivated by the observed undesired characteristics at advanced controller implementations.

The imperative requirements of a rehabilitation prototype do also represent the major bottlenecks in a robotic rehabilitation project. Any design step should be carefully elaborated so that

safety requirement is not violated. Safety should also be preserved while implementing human in the loop controllers. Another complication is caused by the nature of the project; it requires multiple disciplines to work together. In our case, collaboration with therapist could only start with the third version and it requires high amount of dedication from each field to maintain. Furthermore, the delicacy of performing clinical trials with patients requires approvals from not only ethical boards of each constitution but also government structures such as health ministry.

Knowledge Encapsulation

In the case study, the following main steps have been followed for the analysis and reverse engineering of the design process in terms of abstract problem-solving principles:

1) Improvements in the robot were extracted for each design version

2) The designers (second and third author) were interviewed to understand why they performed those improvements

3) For each design version, the conflicts that triggered the improvements were determined based on features and the contradiction matrix of TRIZ

4) The solution implemented was already found is matched with the specific solution that TRIZ suggests for that contradiction

5) The process was visualized as a graph.

In this case study, it was found that the improvements that were made without TRIZ in mind, had actually implemented TRIZ principles for conflict resolution and product design improvement. Thus the complete evolution of the product's design has been reverse-engineered, and represented as explicit information using the presented methodology.

The design process that was revealed through the described reverse-engineering is shown in Figure 1. The database for the encapsulated knowledge on the design process is given in Tables 1 and 2.

TRIZ in the First Step

The first step where TRIZ was applied was the improvement of the robot from version 1 to version 2. In the first version of the AssistOn-Wrist robot, named RiceWrist, cable-driven motors were used for linear motion; direct drive motor was used for forearm pronation/supination; universal bearings combined with a revolute joint were used for spherical joints; and joint space position controller was used as the controller (Figure 2).
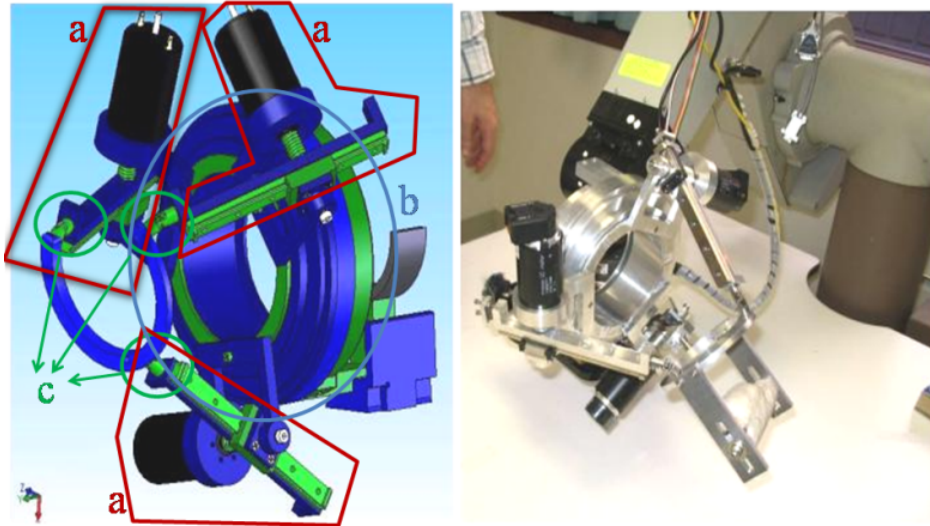

FIGURE 2. FIRST VERSION OF THE ASISTON-WRIST ROBOT. RICEWRIST [35]
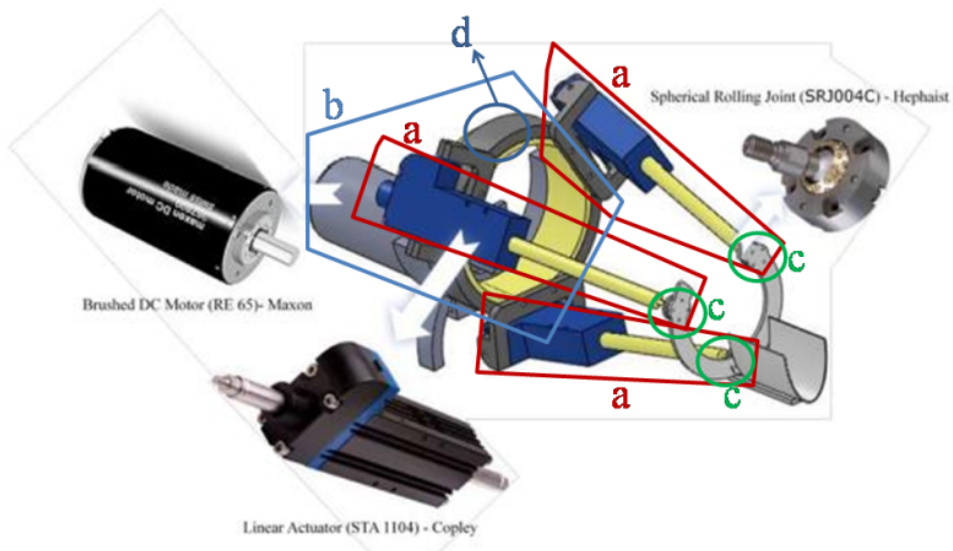

FIGURE 3. SECOND VERSION OF THE ASISTON-WRIST ROBOT [37]

In the second version of the AssistOn-Wrist robot, linear motors were used for linear motions (shown with (a) in Figures 2 and 3); capstan-drive (b)was used for forearm pronation/supination; spherical rolling joint(SRJ) (c) bearings were used instead of universal plus revolute joints. Optimal dimension synthesis was carried out as well as the implementations of task space controller and impedance controller with virtual reality environment (Figure 3).

Improvements that were made between versions 1 (Figure 2) and 2 (Figure 3) were the replacement of cable-driven motor with low friction direct-drive motors, and the combination of universal and revolute joints with spherical joints. By considering TRIZ technique, first contradiction for using linear motor instead of cable-driven (a) was found as the following: improving efficiency (goal 39) is desired feature without having increase in weight of a non-moving object (goal 2). The solution of this contradiction by TRIZ is found by using the contradiction matrix [18]. Obtained solution principles by looking at the contradiction of productivity and weight of stationary object were principles 28, 27, 15 and 3. By analyzing these solutions and looking at the improvements in version 2, it was discovered that principle 15, which is "Dynamics", was applied as a solution. This modification increased quality with higher back drivability and decreased the number of elements by replacing a combination of 'rotational motor with capstain drive' with a single linear motor for each leg. Therefore, this principle was selected as the solution principle for this improvement.

Second contradiction was resolved by using capstan-drive for the serial revolute joint near the base instead of direct-drive motors (b). Improving power (goal 21) was desired without losing reliability (goal 27), in terms of back drivability. The solution of this contradiction by TRIZ can be found by again referring to the contradiction matrix. Obtained solution principles with power as improving one and reliability as worsening one are principles 19, 24, 26, 31. By analyzing these solutions and looking at the improvements in version 2, principle 26, which is "Copying", was the solution because it is defined as using inexpensive, more suitable objects instead of expensive object. Capstan drive motor is less expensive compared to direct drive motor.

Third contradiction related to using SRJ bearing instead of universal and revolute joints (c). Here, the difficulty of control complexity (goal 37) was discovered to be the improving feature and loss of energy (goal 22) was the degrading feature. Improving control was desired without increasing friction. The solution of this contradiction by TRIZ can be found by using contradiction matrix. Obtained solution principles by looking at difficulty of detecting and measuring as improving feature and loss of energy as worsening are principles 35, 3,15,19. By analyzing these solutions and looking at the improvements in version 2, principle 3, which is "Local Quality", was found as the solution, because it aims to make each part of an object function in conditions most suitable for its operation.

Since, universal bearings with revolute joints have control problems, replacing them by SRJ bearings makes operation of the robot more functional.

These three improvements are displayed in Figure 1 within the box "TRIZ in Step 1". There are three vertical columns of nodes in this box, referring to the TRIZ principles that can be applied to resolve the contradictions at that improvement level.

TRIZ in the Second Step

The second step where TRIZ was applied was the improvement from version 2 (Figure 3) to version 3 (Figure 4) of the robot. In version 3 of the AssistOn-Wrist robot, aluminum profiles were used at static bodies for support, while open forearm and wrist rings were implemented for ease of attachment (d).THK curved slides were used at the forearm pronation/supination open ring, so that the rotational motion near the base can be realized. In order to minimize the deteriorating dynamic effects, weight of the dynamic parts should be minimized. This is implemented with the usage of carbon fiber parts, while motors orientations are reversed for smaller connecting parts. It is desired to have robust but low weight wrist and motor holder parts, which are comparatively complex to manufacture because of their inclined surface in more than one plane. Therefore they were produced using steel prototyping with honeycomb structure. The inclined surfaces were calculated with workspace optimization in order to obtain the largest range of motion without compromising the advantages of the optimal dimension optimization (Figure 4).Improvement with respect to version 2 of the robot were using open forearm and wrist rings for easy attachment, and using THK curved slides for rotational motion in pronation/supination instead of capstan-drive motor (d).
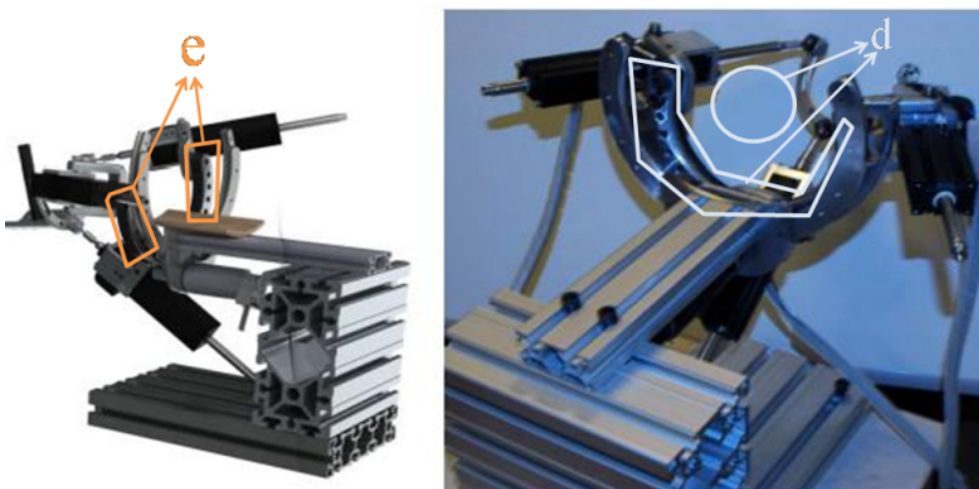

FIGURE 4. THE THIRD VERSION OF THE ASISTON-WRIST ROBOT

The contradiction in this improvement step was discovered to be the ease of attachment as improving feature and power (goal 21) as worsening feature. Here, ease of attachment (goal 33) is a desired feature, but without decreasing power. Obtained solution principles by referring to the contradiction matrix for the contradiction between ease of operation and power are principles 34, 35, 2, 10. Proper solution is determined as based on principle 34, which is "Rejecting and regenerating parts". This principle eliminates an object if it has fulfilled its function. As a result, removing of rolling bearings from the system and replacing them with curved slides provides much easier attachment (d).

TRIZ in the Third Step

The third step where TRIZ was applied was the improvement of the robot from version 3 (Figure 4) to version 4 (Figure 5). Version 4 of the AssistOn-Wrist robot includes parts that do not contain any carbon fiber, uses a new designed capstan ring, and implements quaternion control and PVFC controller. The improvement in this design state is removing of carbon fiber from the system (e).
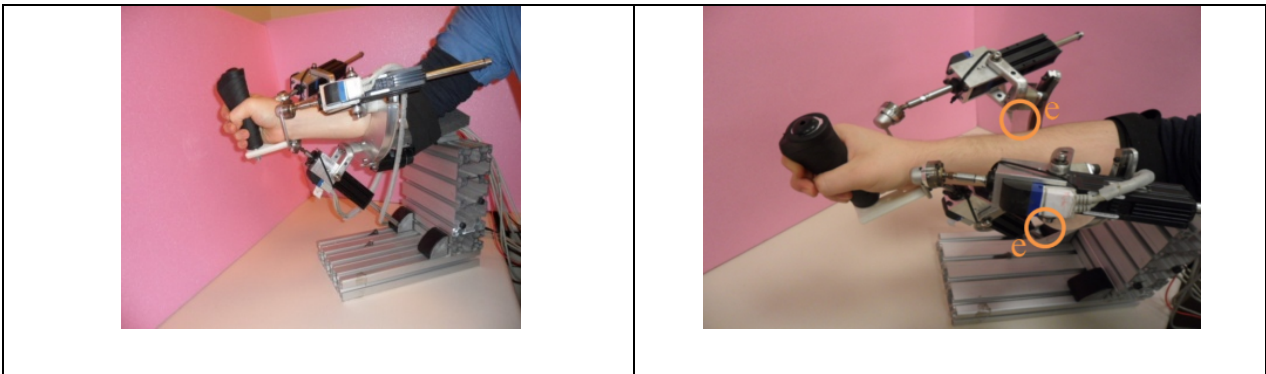

FIGURE 5. THE FOURTH VERSION OF THE ASISTON-WRIST ROBOT [36]

Therefore, the final contradiction was the amount of substance (goal 26) as improving feature and strength (goal 14) as worsening feature, because removing carbon fiber is related to reducing quantity of materials in the robot, whereas carbon fibers are robust materials. Possible solution principles to resolve this conflict are principles 14, 35, 34, 10. The solution implemented here was again principle 34, namely "Rejecting and regenerating parts". As it was explained in previous design improvement, principle 34 suits for the following situation, since removing carbon fibers from the

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system is crucial in terms of aesthetics. Here, the motivation was the difficulty of processing the carbon fiber parts with good precision. The design team had initially implemented carbon fibers in earlier versions because they are robust and low-weight. But the design was then and the carbon fiber component (e) was removed completely, due to production issues. While the new design is slightly heavier than the one with carbon fibers, it has a smaller quantity of substance and achieves better quality resolving the contradiction.

CONCLUSIONS

This paper introduced a knowledge encapsulation and representation methodology, based on TRIZ principles, for the evolution of an engineering system. A case study was presented, where the design process for a wrist rehabilitation robot was extracted and represented as a graph and as a database. The proposed approach and methodology can be used to represent the design process at an abstract level, in terms of a finite number of TRIZ principles, and can be used in guiding future product design process.

This research actually has formalized the approach of Altschuller, who discovered TRIZ through observing 2 million patents. Having an established formal method of capturing how TRIZ is applied through the successive stages of the design process, product designs can now be expressed not in terms of the components implanted, but the design processes that were employed.

This research also opens up the opportunity for applying data mining [38] and network research [39] methods at full scale for analyzing data on the product design process. Hence, much richer insights can be discovered on design processes, which can improve future product design processes and the resulting designs.

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