AC 2012-3431: DESIGNING NOVEL NONDESTRUCTIVE ATTACHMENT METHODS: A METHODOLOGY AND APPLICATION TO ENERGY HARVESTING SYSTEMS

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Designing Novel Attachment Methods: A Methodology and Application to Energy Harvesting Systems

Abstract

In many cases, design involves adding and integrating additional functionality to an existing system. Often, such additions are accomplished by literally attaching a new component or set of components to the existing product. Examples include adding a protective cover to a cell phone, adding an electric starter system to a lawn mower or adding an energy harvesting system to a bridge or other existing infrastructure to provide power for lights or sensors. In many cases, we require that these "add-on" systems interface with the existing system in a nondestructive manner. In some cases, the system should be not affected in any permanent fashion by the attachment. In other cases the requirement is that the system's primary functionality should not be degraded by the attachment.

This paper reports on our work to develop a methodology that will assist designers, including students pursuing engineering degrees, in designing the means of an attachment of a new (child) system onto an existing (parent) system. Based on a literature review of existing joining and attachment methods, we analyze Theory of Inventive Problem-Solving (TRIZ) principles that can be used to design nondestructive attachment methods. In developing the methodology, we performed an experiential study wherein several off-the-shelf products, patents, and biological systems encompassing a wide range of attachment methods were examined. Generalizable patterns from these products were identified and the distinguishing characteristics of each attachment method utilized to develop a foundation for the methodology. A matrix mapping the attachment methods and the system characteristics is presented as a design tool. Use of the tool is demonstrated through its application for attachment of a "child" energy harvesting system to a "parent" existing bridge for the purpose of powering a structural health monitoring system on the bridge.

The effectiveness of the design tool was confirmed through the results of a design experiment where two groups of undergraduate senior engineering students at the US Air Force Academy were presented with a design problem. The control group did not use the new methodology while the experimental group did utilize this methodology to generate concept variants. The attachment concepts from the two groups were compared and analyzed with respect to a number of metrics. The experimental group produced a set of concepts that were higher in quantity, more feasible, and better met the design requirements when compared to the control group. The method should have particular applicability for student design teams where, due to the relatively short design timeline (either 1 or 2 semesters), it is common for the design problem to entail incorporating a "child" system into an existing "parent" system. The overall approach to this research and design-educational-ideation tool promises to inform similar approaches to educational research on innovation processes and students' innovation skill sets.

Introduction

Students enrolled in capstone engineering design courses are often faced with design tasks that involve adding or integrating a new device, subsystem, or part onto an existing system while meeting strict design requirements. Designing an attachment mechanism between these two systems that meet these design requirements may often be difficult and/or time consuming for students in engineering capstone courses where time is a limited resource. In most of these design projects, the system requirements shape the overall design and selection of the attachment mechanism. A methodology to design attachment mechanisms that meet system requirements would be useful for students enrolled in capstone engineering courses in order to increase the quantity, quality, variety and novelty of their ideas.

It is important to first define the system components that are involved in the attachment process. We termed the device, part, or subsystem to be attached the "child", while the existing system, part, or device that the child will attach to was called the "parent." An important characteristic distinguishing the parent from the child was that the parent was always designed independently of the child while the child may or may not have been designed specifically to the parent. Seen below in Figure 1 are some common products that exemplify this parent/child attachment system.   As an example in Figure 1, the doorway is be considered the "parent" while the pull-up bar is the "child" that was specifically designed for the door.

Doorway pull up bar

Suction cup cheese grater

Velcro strapped bulletproof vest

Bathroom shower rod

Side window deflector

Bicycle lights

Figure 1: Products including or containing parent/child attachment systems

Capstone engineering courses require students to use their fundamental engineering knowledge to solve a "real world" engineering problem or to develop a viable product in a one or two semester design project. Often times, these design projects are time consuming as students spend an excessive amount of time designing attachment systems that may not always meet the system requirements, or could be simplified. In addition, students may find that they should focus much of their time and efforts in another more crucial area of the project. These design teams would likely prefer an attachment that works well for their needs although it may not be novel or creative in itself. This methodology would help these students to more quickly select the most viable attachment methods for their design scenario. There are also other design projects where there may not be an “off the market” attachment solution for their particular application. This methodology would help students facing this issue in generating novel and creative solutions. Therefore, the primary aim for this design methodology is to aid students in capstone design courses with the selection and design of attachment systems that are novel, feasible, and meet system requirements. This design tool could also be employed by designers in general that encounter attachment circumstances in other contexts.

There are many capstone design problems where the selection of the attachment mechanisms is crucial. A classic capstone design problem is the wall climbing robot which can move on sloped or vertical structures to perform operations that reduce risks to humans. It is a challenging mechatronics problem where researchers have investigated many different attachment mechanisms such as electrostatic adhesion[1], magnetic bases[2], and suction[3]. One capstone design project at the University of California, Santa Barbara paired up a student group with a bio-medical company to design and prototype a medical instrument that must attach anddetach to a cervical plate[4]. In this project, students must select and design an attachment mechanism with specific load requirements. Another capstone design project at Northwestern University had students redesigning a quick-release paint roller frame for a painting tools manufacturer[5]. Students were required to design a robust quick-release mechanism that easily attached the roller to the frame.

Background

Research into the current body of literature concerning attachment mechanisms revealed that several approaches exist on the selection, generation, and design of connections. Ehrlenspiel developed a generic seven-step process for the design of connections that focused on selecting available connections and dimensioning them[6]. Roth, in the context of his renowned work on kinematics, developed matrices representing free and restricted movement between components[7]. Roth also developed design catalogues that classify existing connections according to different criteria and support the designer in selecting the best solution variant. For the design of novel connections, Roth proposes the use of a morphological chart where the connection properties are the vertical columns and the corresponding fastener properties are on the horizontal rows[7]. Roth classified the various attachment methods into three distinct types of locking: material, form, and force. Brandon and Kaplan classified connections as mechanical, chemical, or physical[8]. Each of these connection classifications helped ultimately shape our method of classifying attachment mechanisms. Koller defined a connection as one of fourteen physical effects restricting movement, the material of the components, and the geometry of the connection[9]. Klett developed an approach to design connections for assembly and disassembly by classifying different locking and unlocking mechanisms[10]. Overall there have been various research efforts in developing a structured approach for the design of connections but none specifically for use in engineering education.

Research Approach

An inductive approach was used to gather and study attachment principles found most commonly in existing products, patents, and nature. These attachment principles formed a basis for an empirical study, where the underlying assumption is that there are attachment methods that are used implicitly across many products. The systematic classification of these methods has not been formalized for use in a design methodology. This approach has been used before to study, define, and categorize transformation principles as part of an innovative design process[11].Figure 2 demonstrates the research process taken using a flowchart.

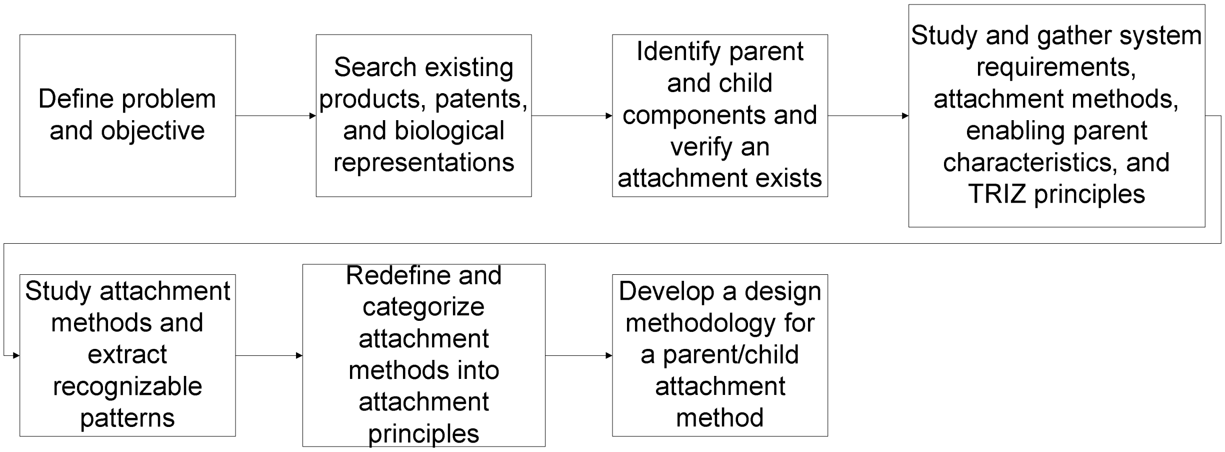

Figure 2: Flowchart of inductive research process

To determine the number of products, patents, and biological examples sufficient to capture the majority of attachment principles primarily within the mechanical domain, the number of unique attachment principles discovered was graphed. Figure 3 shows that no new principles were derived after only examining 26 examples. A total of 50 examples were analyzed. While it can be assumed that not all principles were discovered, especially among the material and field domains, a very high percentage of attachment principles in the mechanical domain were discovered.

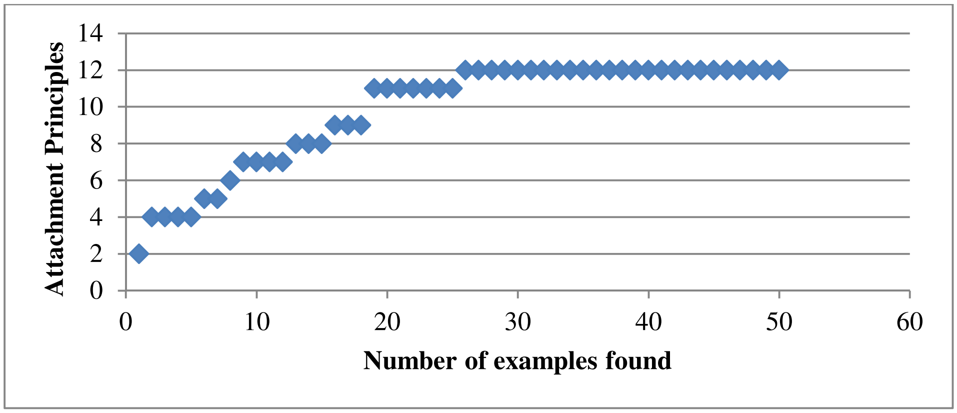

Figure 3: Number of unique attachment principles found

Attachment Methods

The full list of attachment principles can be found in Appendix A. It should be noted that the attachment principles in the mechanical domain are more generalized compared to the material and field domains. For example, the axial expansive principle includes products such as a shower rod and a car jack. Both products functionally expand in an axial direction to form the attachment even though they serve two very different purposes. Listed in Appendix B are the definitions and examples of the mechanical attachment principles which were used in the design experiment. Also listed are the “enabling parent characteristics” which are features of the parent that serve as indicators to whether or not a particular principle is a viable option.

Methodology

After gathering and categorizing the attachment principles, a methodology was needed that would narrow the list of suitable attachment methods based on both the child and parent system requirements. Several methods were considered and ultimately a matrix that maps the system requirements directly into the attachment principles was selected. Since there exists a direct mapping between the system requirements (non-destructive, permanent, removable) and the attachment principles, this relationship could be used to form the basis for the methodology tool.

From the fifty products surveyed, the system requirements and attachment principles were gathered and recorded. A matrix was created of the system requirements versus the attachment principles. Each product had multiple system requirements and attachment principles. The number of occurrences of an attachment principle and system requirement appearing together in a product was recorded. Each element in the matrix was divided by their respective column total to produce a score. For any given column (system requirements), the attachment principles with higher scores were better candidates for the given scenario.

Design Experiment

In order to test the effectiveness of the methodology as a design tool, we conducted a design experiment on a group of senior engineering students at the US Air Force Academy. The motivation for this experiment was to examine the effect of using the attachment principles on the students' ability to generate design concepts that are novel, feasible, and meet system design requirements.

A group of eight students were evenly divided into control and experimental groups. The experiment was implemented in three phases. For the first phase, the students in both groups were given the same prompt to design an attachment for a wind energy harvester onto a bridge. The drawings for the bridge and the wind energy harvester were given on a separate sheet and can be found in Appendix C. In addition, a set of system requirements, which are listed below, were also given to all students.

System Requirements

- No permanent alterations to the bridge
- No part of the wind harvester can hang below the lowest part of bridge
- No part of the wind harvester can be on the driving surface of the road and it cannot interfere with bridge traffic
- Total weight of the system should be less than approximately 20 lbs.
- Time to install should be less than 1 hour
- Service life of attachment should be at least 10 – 15 years
- Device should be portable and easy to install with minimal tools

The students in both groups were given fifteen minutes to generate as many attachment concepts in the form of sketches, diagrams, figures, and text to help explain their ideas. The students were also told to clearly state any assumptions made in generating solutions so they would not be restrained in producing novel or extreme ideas.

During the second phase, the control group was given an article from a sustainable design journal (used as a distraction) while the experimental group was given the set of attachment principles from the mechanical domain along with the enabling parent characteristics and a set of examples and can be found in Appendix B. Each group had fifteen minutes to review their respective materials. No sketches or designs were produced during this phase.

The experimental group also reviewed a set of TRIZ principles which were directly applicable to the design problem. The intended purpose was for these TRIZ principles to aid students in generating solutions to some of the design conflicts stemming from the system requirements. This was accomplished by converting the design requirements into a conflict of generalized engineering parameters. These parameters were derived from Altshuller's 39 generalized engineering principles[12]. These principles were then selected from Altshuller's matrix of contradictions. The top five principles which were most likely to solve these conflicts were selected and given to the experimental group accompanied with an explanation and example for each TRIZ principle. The set of TRIZ principles are listed in Appendix B.

During the third phase, the control and experimental groups both had fifteen minutes to generate additional concepts. The system requirements and dimensions did not change from phase 1. The experimental group was allowed to reference the attachment and TRIZ principles and both groups could reference the bridge and wind harvester drawings.

Design Metrics

Four design metrics were used to measure the effectiveness of the concepts generated: *quantity, quality, novelty,* and *variety*[13]. The descriptions of the metrics and how they were used to evaluate the generated ideas are explained below.

> *Quantity*: The total number of ideas generated by an individual student or control group. The justification for this metric is that an increase in the quantity of ideas will also increase the probability of better ideas being generated. This metric will be used to evaluate any significant increase in the number of ideas between the first and second phases among both the experimental and control groups. An increase in percentage of ideas for the experimental group would suggest some degree of efficacy in the proposed methodology. Note that in order to have some uniformity regarding this quantity metric, the evaluators counting the number of ideas are instructed to increment their count only if the proposed new idea meets one of the primary functions of the system using a different embodiment.
>
> *Quality*: The number of ideas that exhibit a satisfactory degree of feasibility. The justification for this metric is that regardless of the number or variety of generated designs, they are useless if they are not reasonably feasible or achievable in practice. This metric will be assessed by a percentage of feasible designs that will be averaged among the four evaluators. An increase in percentage of quality for the experimental group would suggest some degree of efficacy in the proposed methodology.
>
> *Novelty*: The number of unique categories where there are at most two designs classified from separate individuals. The justification for this metric is the idea to think "outside-the-box" into a design space that isn't commonly explored in order to formulate radical and unique designs. The idea of creating unique designs won't have a direct relationship with feasibility, but it will increase the likelihood of a never-seen-before design that solves the problem in a different way using metaphors and analogies. This metric will be assessed by a percentage of the categories where there are at most two classified designs, and averaged among the four evaluators.

Variety: The number of unique categories under which the designs are classified. The justification for this metric is to verify how well the overall design space has been explored, in order to counterbalance the *quantity* metric. A good design space will have a large quantity spread across various categories. A category in this given problem statement is classified as a design exhibiting a specific type of attachment as well as attachment location. This metric will be assessed by classifying each individual design under a category based on type of attachment and attachment location and averaging the number of categories counted among the four evaluators.

The evaluators had to assess the generated designs according to the metrics delineated above with an established perspective in mind. In order to assess the ideas successfully, the design requirements from the original problem statement had to be taken under consideration, such as no permanent alterations to the bridge, or no part of the wind harvester can interfere with bridge traffic. This is especially crucial when evaluating *quality* as to whether or not a given design will be acceptable according to the given requirements.

Four evaluators assessed the four metrics with the design requirements in mind across all the designs from the control and experimental groups. The results are shown below.

Results

The average percentage of designs that exhibited each metric as well as their standard deviations were gathered from the four evaluators and presented in the Table 1 below. Control 1 and Exp. 1 refer to the first time period given to the teams to generate ideas. Control 2 and Exp. 2 refer to the second time period (after the experimental group had been exposed to the method).

		Control 1	**Control 2**	**Exp. 1**	**Exp. 2**
Quantity	**Designs**	**16**	**18**	**19**	**24**
Quality	**Average**	**72.2%**	**73.9%**	**88.5%**	**62.3%**
	St. Dev.	**9.5%**	**8.5%**	**10%**	**8.1%**
Novelty	**Average**	**35.5%**	**30.2%**	**35.9%**	**30.5%**
	St. Dev.	**5.0%**	**3.9%**	**5.9%**	**7.1%**
Variety	**Average**	**35.1%**	**39.8%**	**45.4%**	**40.5%**
	St. Dev.	**7.6%**	**5.1%**	**2.8%**	**5.5%**

Table 1: Average percentage quality, novelty, and variety of designs that exhibited *quality*

The results in the above table display an acceptable standard deviation among the four evaluators, so the evaluation did not have to be repeated. The percentage increases and decreases of designs that exhibited each individual design metric within both the control and experimental group are displayed in the chart below. Note that a more formal study is planned where additional evaluators will be employed and statistical inter-rater reliability computations will be completed.

Design Metric	**Percent Increase**	
	Control Group	**Experimental Group**
Quantity	**12.5%**	**26.3%**
Quality	**-30.0%**	**2.3%**
Novelty	**-14.9%**	**-15.0%**
Variety	**13.7%**	**-10.7%**

Table 2: The percentage increases between the first and second design phases within each group

The results from Table 2 indicate that the experimental group formulated more designs than the control group after they were introduced to the methodology according to the *quantity* metric. The *novelty* metric exhibited an approximately equal decrease across both groups, indicating that the methodology has no significant effect on the novelty of generated ideas. Both groups produced their most novel designs in the first design phase. The table also shows that the control group produced more designs that exhibited the *variety* metric. This suggests that the experimental group did indeed follow the suggested attachment principles and produced more designs that belonged in categories directly related to those principles, while the control group had no restrictions and produced designs across more diverse categories.

Although a greater variety may appear to be more beneficial for the control group, not all of these designs were deemed feasible. Probably the most interesting and significant design metric to observe is the *quality* metric. For the control group, there was a 30% decrease in quantity of designs that were by definition feasible, as opposed to a slight 2% increase in the experimental group. This indicates that the methodology discussed in this paper introduced key design attachment principles and instigated the experimental group to apply them to their new set of designs. On the other hand, the control group hit a metaphoric wall in terms of coming up with additional feasible designs and had to resort to more unusual and obscure ones with less *quality*.

Furthermore, statistical analysis was performed on the *quality* metric, which embodies the most noteworthy change between the control and experimental group, in order to determine if the percent increases between the two groups is statistically significant for the given sample size. A standard independent Student *t*-test was executed. The *t*-value for the experiment was 2.60, which proves to be higher than the t_p value of 2.44, which can be found in any statistics textbook under the 95% confidence interval[14]. This proves that the results associated with the *quality* metric are statistically significant. Furthermore, it can also be stated from the *t*-test that “We are 95% confident that the experimental group will produce at least 2% more and at most 54% more quality designs than the control group.”

Qualitative Assessment

The students in the experimental group composed a qualitative assessment of the attachment principles and the experiment itself. Their responses are shown below.

1. "During the first phase of the experiment, going into the concept variants cold, my ideas were limited to generic that were often one dimensional. I found that the design constraints were daunting and severely hampered broad concept generation. Much of the time allotted during phase one was spent staring at the paper and thinking in endless circles with few actual concepts.

   During the second phase, the document outlining various and conventional methods of attachment with examples was extremely helpful in opening creative pathways in my brain. Although I was already somewhat familiar with attaching an energy harvesting device to a bridge, I still found the handout very helpful. While reading through the handout, I found myself saying, "ah-ha", with ideas already starting to form in my head.

   The last phase of the experiment resulted in a significant increase in concepts generated, mostly due in part to the second phase. I found myself exploring more avenues of attachment that I previously overlooked. I also found that the design constraints were less daunting than before in the first phase. I gained a more enlightened perspective about how to approach the design problem which enabled me to come up with creative ways to solve the problem."

2. "The method I used when attempting to develop a design for affixing a wind-powered energy harvester to a typical I-truss bridge was extremely effective in opening the design space to creativity in the context of practical and applicable engineering solutions. There are many different design technologies which are currently used to affix one object to another and reading through and being able to visualize some of these concepts before beginning the design process steered my concepts in that direction.

   This methodology was also extremely effective in opening the design space to many more different and unique possibilities. Normally, the 6-3-5 technique lasted too long for our design. I would generate a couple of feasible ideas at the beginning of the exercise and, eventually, I would simply start to repeat the exact same concepts. Visualizing different concepts prior to designing again enabled a much greater degree of feasible creativity and expanded the number of viable prototype concepts."

3. "Brainstorming ideas for methods to attach mounting systems on I-beam type bridges was enhanced by introducing different mounting systems to the designer. Before being shown the different kinds of common mounting systems the designer has to come up with original ideas. During my designs I became focused on only a few concepts and was limited. I was able to manipulate my concepts to design many different mounts.

However, most ideas followed a similar concept. Viewing the mounting concepts of the next section gave a plethora of new mounting techniques and opened up the design space. No longer was I limited to the few concepts for mounting used in the first section. I was able to manipulate and creatively institute the new concepts to get many variations in the designs. There was a noticeable difference in the original designs and the latter designs. The introduction of mounting principles resulted in a broader spectrum of mounting solutions. Broadening the design space is beneficial but the initial creativity given to the designer before being shown mounting solutions should not be avoided. New solutions may be produced by instituting a creative design phase."

4. "After attempting to complete the design challenge the first time, I thought that I was out of ideas. Even after 5 minutes of brainstorming the mental well of creativity seemed to be empty. The pictures that followed gave vague alternate solutions that inspired another full page of ideas. The comparisons to other simple machines and devices allowed me to get past my creative block and resume brainstorming up ideas.

   The descriptions of attachment possibilities were helpful but the most powerful tool was the list of examples that followed each picture. For example, the idea of an expanding force was meaningless to me until the example of a shower rod was given. I then used that principle in several of my designs. The examples give simple solutions that can be applied to many different and unique designs.

   Overall, the experience was painless and helpful to say the least. It was a nice boost of confidence in both me and the project. After the first round of designing, some frustration sets in due to lack of ideas. The pictures and descriptions gave an extra surge and assuaged some of my original fears about not coming up with enough ideas. The process should be continued and applied throughout the entire design and prototyping experience. It would have been nice to do something like this earlier in our creative timeline but overall it was a beneficial, helpful experience. From personal observation it seemed that we fared much better than our counterparts who had no pictures and only bland boring words to read."

The general consensus from the students in the experimental group was that the attachment principles and the accompanying examples were helpful in generating new ideas, more concepts, a broader spectrum of ideas, and in some cases more creative concepts. One of the students even pointed out that the design requirements were less daunting after reviewing the attachment principles. This leads to the conclusion that the methodology appears to help students in meeting design requirements.

Road Ahead

Although the basis for the methodology has been established, more products in the material and field domains should be analyzed and cataloged in the matrix to provide some balance for the mechanical domain attachment principles. In addition, a design experiment with more students and a different set of design requirements should be performed to gain more statistical significance. The ultimate goal is that this methodology would be converted into a usable tool in a classroom setting. A user survey or questionnaire that would deliver the top three attachment principles based on guided questions would be one way of forming the tool. Ideally this tool would both automate design and help inspire students in developing innovative attachment systems.

Conclusion

A methodology to select and design attachment systems that are novel, feasible, and capable of meeting system requirements is presented. A design experiment testing the effectiveness of the methodology as a design tool was conducted. The results from the experiment revealed that the methodology helped student designers to produce concepts that were higher in quantity and quality, and better met the design requirements. However, the methodology also decreased the students' ability in producing a variety of concepts and there was no noticeable difference in the novelty of generated concepts.

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Appendix A – Attachment Principles

Attachment Principle Domains	*Attachment Principles*	*Definition*	*Examples*
Mechanical	Radial Expansive	Applies a radially outward force within a hole	Anchor bolts, Threaded inserts
	Radial Compressive	Applies a radially inward force on an extrusion	Zip ties, Hose clamps
	Axial Expansive	Applies axially outward forces perpendicular to two surfaces	Shower rod, Car jack
	Axial Compressive	Applies axially inward forces perpendicular to two surfaces	Table clamp, Doorway pull up bar
	Hook	Object is suspended through the contact interface between the upward facing surfaces of an extrusion and the downward facing surfaces of an object	Hangers, Backpack
Material	Adhesive Bonding	Reactive: Adhesives that chemically react to harden.	Epoxies, Light-curing materials
		Non-reactive: No chemical reaction required.	Drying adhesives, contact adhesives, hot adhesives
	Coalescence	Attachment where two or more components merge and form a singular part	Concrete, Welding, Soldering, Brazing
	Cohesion	Attachment describing the natural attraction of similar materials	Water molecules, Surface tension
	Chemical Adhesion	Attachment where the two surfaces form ionic, covalent, or hydrogen bonds	Gecko[15], Wet paper on glass
Fields	Magnetic	The components are locked through the attraction of opposing magnetic fields. Magnetic field can be supplied through a permanent magnet or electrically generated.	Magnetic base dial indicator, fridge magnets
	Vacuum	The component interfaces are locked through the difference between ambient pressure and the pressure in the contact cavity	Suction cups, GPS windshield mount
	Electric	Attachment through the attraction between two electrically charged bodies	Electrostatic chuck, static balloon

Appendix B – Mechanical attachment principles and TRIZ principles

Radial Expansive – Attachment principle which applies a radially outward force within a hole.
Examples: Anchor bolts (Fig.4), Press fit threaded inserts (Fig.5), Dowel pin
Enabling characteristics: Hole

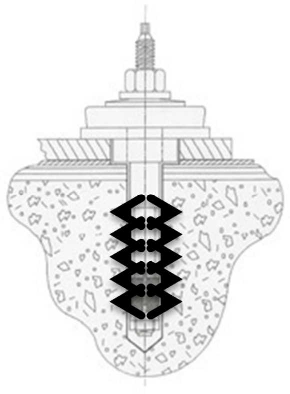

Figure 4: Anchor Bolt

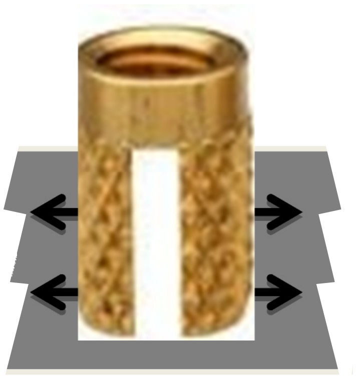

Figure 5: Press fit threaded inserts

Radial Compressive – Attachment principle which applies a radially inward force on an extrusion.
Examples: Zip ties (Fig.6), Hose clamps (Fig.7), Car cup holders
Enabling characteristics: Extrusion

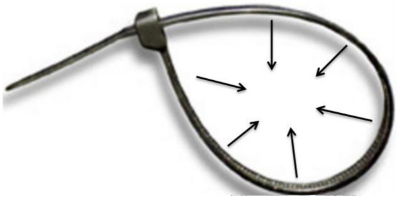

Figure 6: Zip tie

Figure 7: Hose clamp

Axial Expansive – Attachment principle which applies axially outward opposing forces perpendicular to two surfaces.
Examples: Shower rod (Fig.8), Car jack (Fig.9)
Enabling characteristics: Two parallel flat surfaces, two angled flat surfaces

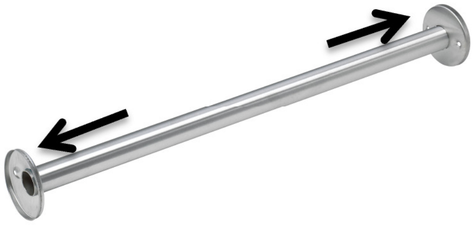

Figure 8: Shower rod

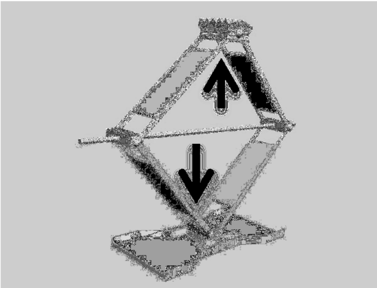

Figure 9: Car jack

Axial Compressive – Attachment principle which applies axially inward forces perpendicular to two surfaces.
Examples: Rivet, Clamp lamp (Fig.10), Pull up bar (Fig.11)
Enabling characteristics: Perpendicular edges, two parallel flat surfaces

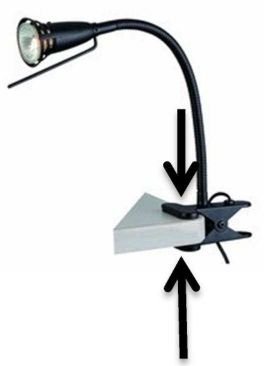

Figure 10: Clamp lamp

Figure 11: Doorway pull up bar

Hook – Attachment principle where the object is suspended through the contact interface between the upward facing surfaces of an extrusion and the downward facing surfaces of the object.
Examples: Hanger (Fig.12), Backpack (Fig.13), Velcro (Fig.14)
Enabling characteristics: Extrusion

Figure 12: Hanger

Figure 13: Backpack

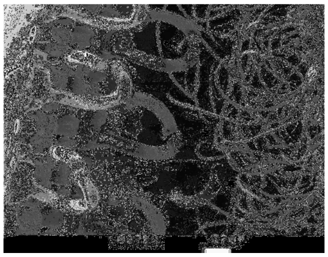

Figure 14: Magnified view of Velcro

TRIZ Examples

Principle of segmentation – To make a product easier to disassemble and more portable, consider dividing the object into many independent parts.
Examples: Temporary Street light connected with flexible joints (Fig. 15), Development of a roller conveyor with multiple rollers (Fig. 16)

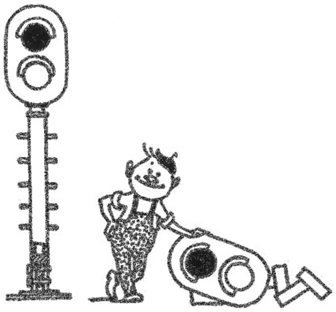

Figure 15: Street light pole

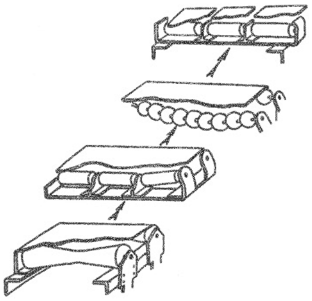

Figure 16: Roller conveyor

Principle of moving into a new dimension – Increase the degrees of freedom of the attachment so that the object can be oriented in many different ways. Use a multi-layered assembly instead of a single layer. Incline the object or turn it on its side. Use the other side of an area.
Examples: Robotic Arm with multiple degrees of freedom (Fig. 17), Multi-layered shelf (Fig. 18)

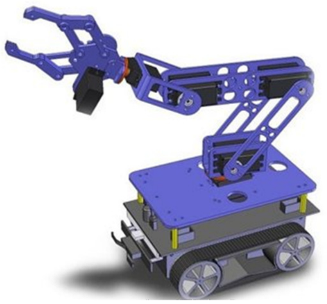

Figure 17: Robotic arm with multiple DOF

Figure 18: Multi-layered shelf

Principle of universality – Let one object perform several different functions. Remove redundant objects.
Examples: Hat being used as a handbag (Fig. 19), Luggage handle being used as an iron (Fig. 20)

Figure 19: Handbag/Hat

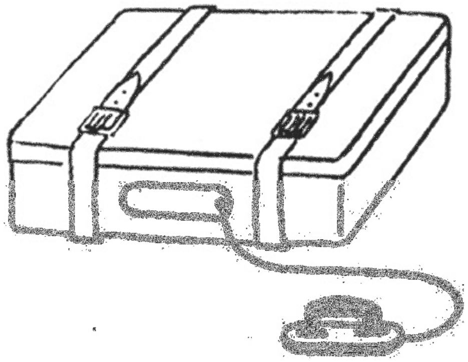

Figure 20: Luggage handle/Iron

Principle of counterweight – To make the product more stable and balanced in weight, consider using counterweights.

Examples: Chalkboard being raised/lowered with counterweights (Fig. 21), Crane staying upright through counterweights (Fig. 22)

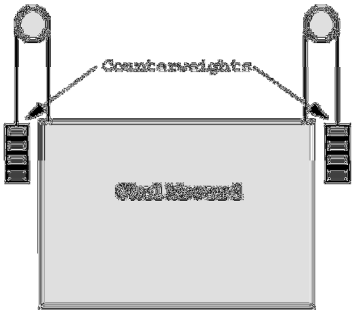

Figure 21: Chalkboard

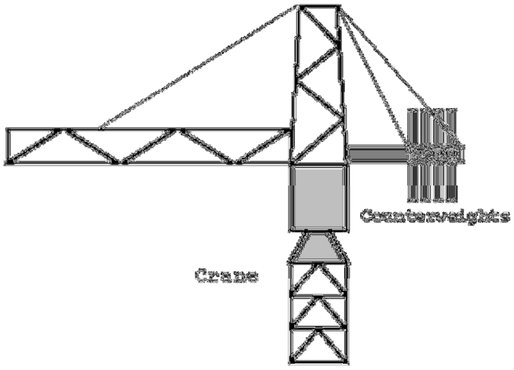

Figure 22: Crane

Principle of introducing protection in advance – To increase the reliability of the product, introduce protections against accidents before the action is performed.

Examples: Protection (Anchors) in lead climbing (Fig. 23), Fuses designed to limit excess current draw (Fig. 24)

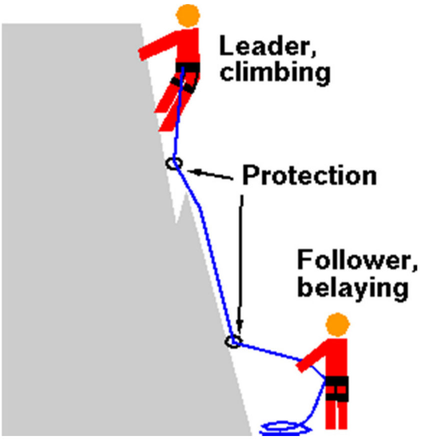

Figure 23: Lead climbing protection

Figure 24: Fuses

Appendix C – Bridge and wind energy harvester drawings