Nondestructive methods of integrating energy harvesting systems for highway bridges

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ABSTRACT

Designing an attachment structure that is both novel and meets the system requirements can be a difficult task especially for inexperienced designers. This paper presents a design methodology for concept generation of a “parent/child” attachment system. The “child” is broadly defined as any device, part, or subsystem that will attach to any existing system, part, or device called the “parent.” An inductive research process was used to study a variety of products, patents, and biological examples that exemplified the parent/child system. Common traits among these products were found and categorized as attachment principles in three different domains: mechanical, material, and field. The attachment principles within the mechanical domain and accompanying examples are the focus of this paper. As an example of the method, a case study of generating concepts for a bridge mounted wind energy harvester using the mechanical attachment principles derived from the methodology and TRIZ principles derived from Altshuller’s matrix of contradictions is presented.

Keywords: Design Methodology, Concept Generation, Attachment Systems Integration, Energy Harvesting, Wind Turbine Attachment, Structural Health Monitoring, Bridge Attachment, Connections

1. INTRODUCTION

Design engineers often face design problems 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 student, designer and practicing engineers. In most of these design projects, the system requirements shape the overall design and selection of the attachment mechanism. A methodology specific to the design of attachment systems would be useful for designers 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. The device, part, or subsystem to be attached is termed the “child”, while the existing system, part, or device that the child will attach to is termed the “parent.” An important characteristic distinguishing the parent from the child is that the parent is always designed independently of the child while the child may or may not be designed specifically to the parent. Seen below in Figure 1 are some common products that exemplify this parent/child attachment system.

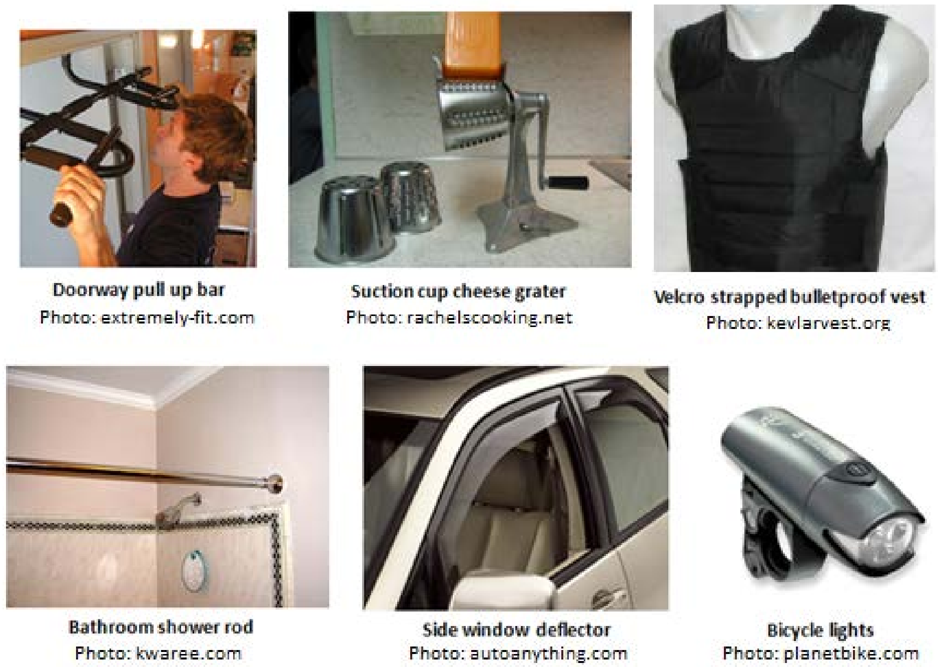

Figure 1: Products including or containing parent/child attachment systems

Engineers can spend an excessive amount of time designing a parent/child attachment system that does not meet the system requirements, can be simplified, or already exists. Designers may find they are distracted from more crucial areas of the project. We propose a methodology to help designers to more quickly select the most viable attachment methods for their design scenario. There are also many design projects where there may not be a viable commercial off-the-shelf (COTS) attachment solution. Our methodology helps designers facing this issue to generate novel and creative solution concepts. The primary aim for this design methodology is to aid engineers with the selection and design of attachment systems that are novel, feasible, and compatible with system requirements.

There are many engineering design problems where the selection of the attachment mechanisms is crucial. A classic design problem is the wall climbing robot which can move on sloped or vertical structures to perform operations that reduce risks to humans. This 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 design project at the University of California, Santa Barbara paired a student group with a bio-medical company to design and prototype a medical instrument that must attach/detach to a cervical plate[4]. In this project, students selected and designed an attachment mechanism with specific load requirements. Another engineering 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.

2. 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 focuses on selecting available connections and dimensioning them[6]. Roth 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]. These various research efforts all seek to develop structured approaches for the design of connections but none specifically address non-destructive integration for energy harvesting.

3. 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 the 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 illustrates this research process. It should be noted that the “enabling parent characteristics” listed in box 4 of Figure 2 are defined as features of the parent that serve as indicators to whether or not a particular principle is a viable option.

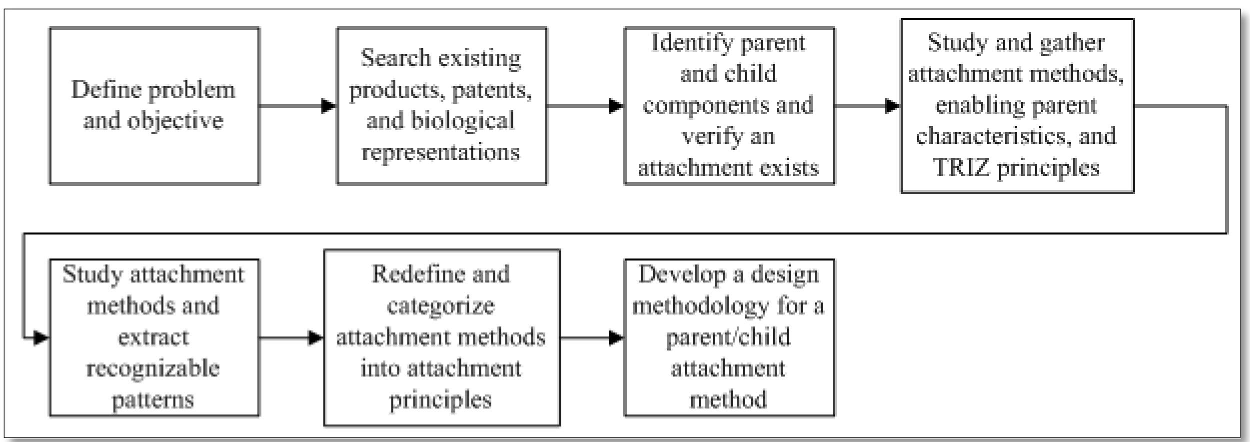

Figure 2: Flowchart of inductive research process

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 examining only 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 appear to have been discovered. These principles were then studied and classified according to their domain.

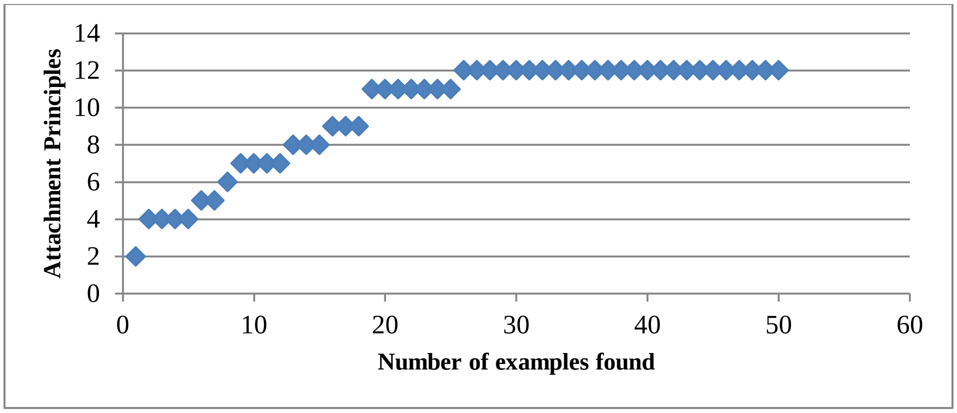

Figure 3: Number of unique attachment principles found

3.1 Attachment Principles

The full list of attachment principles can be found below in Table 1. 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.

3.2 Examples of mechanical attachment principles

Listed below are the definitions and examples of the mechanical attachment principles which were used in the case study.

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

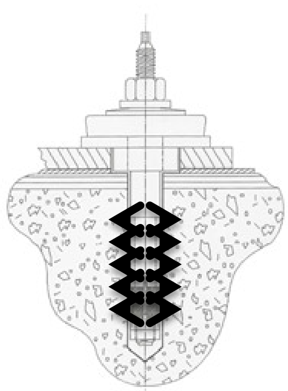

Figure 4: Anchor Bolt

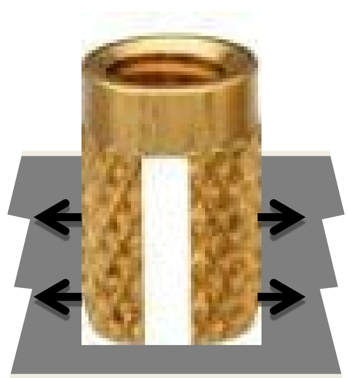

Figure 5: Press fit threaded inserts

Table 1: Attachment principles sorted by domain

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	Attachment principle where the object is suspended through the curved or bent contact interfaces of an extrusion and 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

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

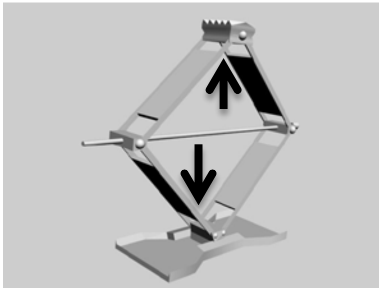

Figure 9: Car jack

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 curved or bent contact interfaces of an extrusion and an object.
Examples: Hanger (Fig.12), Backpack (Fig.13), Velcro (Fig.14)
Enabling characteristics: Extrusion

Figure 12: Hanger

Figure 13: Backpack

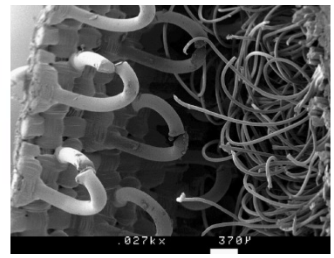

Figure 14: Velcro

3.2 Methodology

After gathering and categorizing the attachment principles, a methodology was developed to narrow the list of suitable attachment methods based on the 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 its respective column sum to produce a normalized score. For any given column (system requirements), the attachment principles with higher scores were better candidates for the given scenario.

4. CASE STUDY: WIND ENERGY HARVESTER

A case study was conducted in order to test the effectiveness of the methodology as a design tool. The design goal of this case study was to non-destructively attach a wind energy harvester to any portion of the bridge. Additionally, the case study was selected to demonstrate the variety of feasible design concepts that can be generated using the attachment methodology described in the previous section. A set of requirements, listed below, was given before the brainstorming phase occurred.

System Requirements

- No permanent alterations to any portion of the bridge
- No part of the wind harvester can hang below the lowest part of bridge (unless it is over water)
- No part of the wind harvester can be on the driving surface of the road and it cannot interfere with bridge traffic
- 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

During the ideation process, different designs for an attachment were conceptualized using different attachment principles or combinations of attachment principles, as well as from a set of principles from Altshuller's Theory of Inventive Problem Solving (TIPS, or TRIZ using the Russian acronym) [12]. The TRIZ method is based on 39 generalized engineering parameters and 40 principles of invention. The designer uses the TRIZ matrix of contradictions to identify the applicable principles of invention for pairs of conflicting generalized engineering parameters. For our purposes, the TRIZ principles were used to aid in generating solutions to some of the design conflicts stemming from the system requirements. This was accomplished by translating the design requirements into pairs of conflicting generalized engineering parameters. These parameters were used to select principles of invention from Altshuller's matrix of contradictions and used in conjunction with the attachment principles. The TRIZ principles specifically used in the designs are defined below. Four attachment systems are presented that best implement the attachment and TRIZ principles.

TRIZ Principles

- *Principle of universality* – Let one object perform several different functions. Remove redundant objects.
- *Principle of counterweight* – Attach an object with lifting power or use the interactions with environment.
- *Principle of segmentation* – Divide the object into independent parts that are easy to disassemble
- *Nesting principle* – Place one object inside another, which in turn is placed inside a third, etc.
- *Principle of moving into a new dimension* – Increase the object's degree of freedom. Use a multi-layered assembly.
- *Copying principle* – Replace an object with multiple copies; make use of scale effects.
- *Principle of opposite solution* – Implement the opposite action of what is specified. Turn the object upside down.

Attachment System #1

This attachment system in Figure 15 uses a U-shaped metal hook to attach to the outer concrete portion of the bridge, implementing the *hook* attachment principle. The system embodies the *axial compressive* attachment principle through screw clamps on both sides of the concrete. A weight is mounted on one side of the system to balance the moments caused by the wind harvester, using the TRIZ *principle of counterweight*. Finally, the TRIZ *principle of universality* was applied based on the fact that the location and attachment type of this system can be integrated with a wind or solar harvester.

Attachment Principles: Axial compressive, Hook
TRIZ Principles: Principle of counterweight, Principle of universality

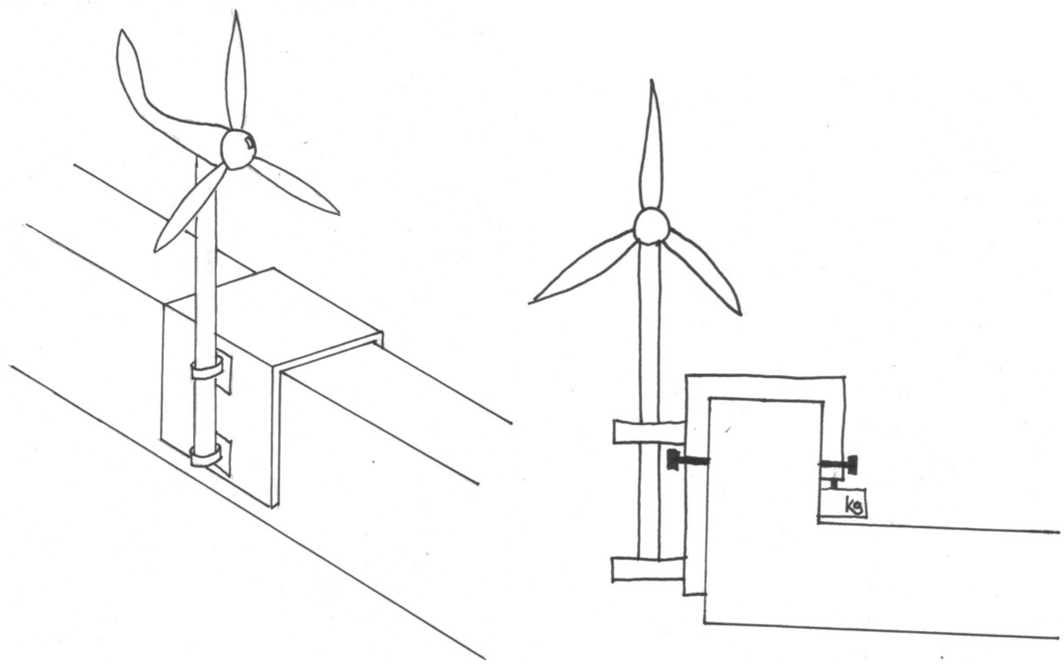

Figure 15: First attachment system with an isometric view (left) and side view (right)

Attachment System #2

This attachment system in Figure 16 is mounted and secured in between the two flanges of an I-beam underneath the bridge using the *axial expansive* attachment principle. There is no physical space for the wind harvester to rotate next to the I-beam, so the TRIZ *principle of moving into a new dimension* was applied to shift the wind harvester further away. The mechanical beams that perform this action were conceptualized using both the *radial compressive* attachment principle and the TRIZ *nesting principle*. Each beam has a smaller beam nested inside in order to change the distance of extension, and both beams are attached to the rod using clamps. Finally, the TRIZ *principle of segmentation* was applied to this system by displacing the rod attached to the wind harvester into two: one for the harvester and one as the attachment system.

Attachment Principles: Axial expansive, Radial compressive

TRIZ Principles: Principle of moving into a new dimension, Nesting principle, Principle of segmentation

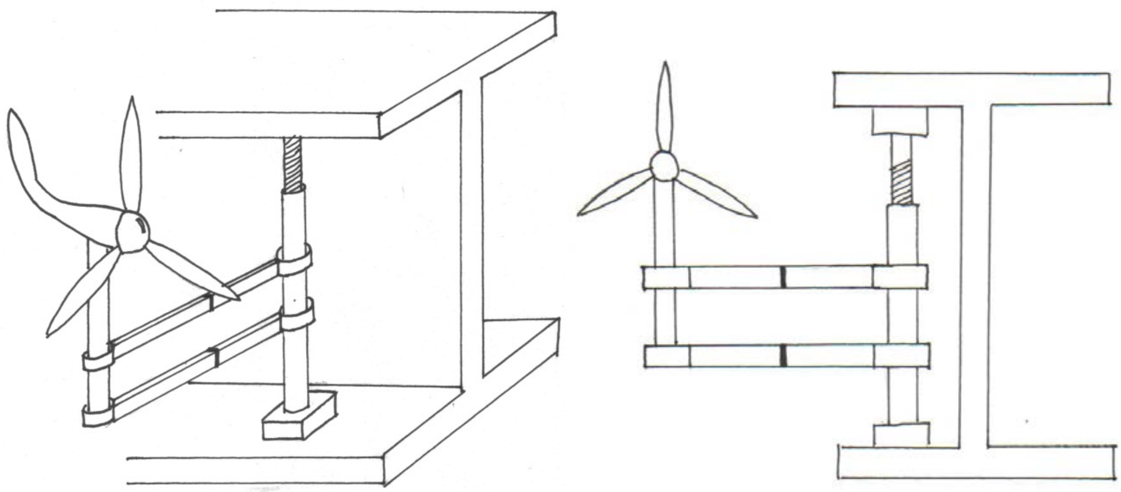

Figure 16: Second attachment system with an isometric view (left) and side view (right)

Attachment System #3

This system in Figure 17 uses the *radial expansive* attachment principle to mount the wind harvester onto bridge, but the enabling characteristic was interpreted as a cavity in the bridge architecture instead of a hole. This way, three rods can radially expand in order to secure the wind harvester to different points on the bridge. The TRIZ *copying principle* was used by replicating the axially expansive rod from Attachment System #2 above.

Attachment Principles: Radial expansive
TRIZ Principles: Copying principle

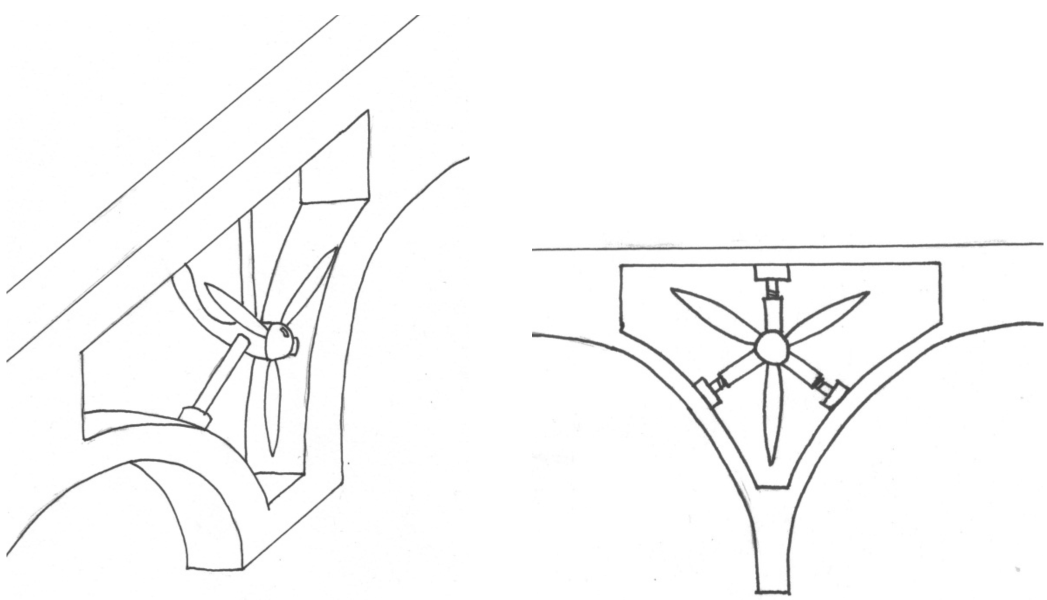

Figure 17: Third attachment system with an isometric view (left) and side view (right)

Attachment System #4

At this point all of the mechanical attachment principles were used in the previous examples, and exhibited a great deal of variety. However, the principles are not limited to these types of solutions. They can be applied again in conjunction with other TRIZ principles in order to embody a larger design space. The following attachment system in Figure 18 uses the *axial compressive* and *hook* principles again, but this time with the TRIZ *principle of opposite solution*. The wind harvester is turned upside down and mounted to the L-shaped cross beam that spans between two I-beams. The wind harvester pole is welded to the metal hook—not the bridge itself—while the metal hook itself is secured to the bridge using screw clamps.

Attachment Principles: Axial compressive, Hook
TRIZ Principles: Principle of opposite solution

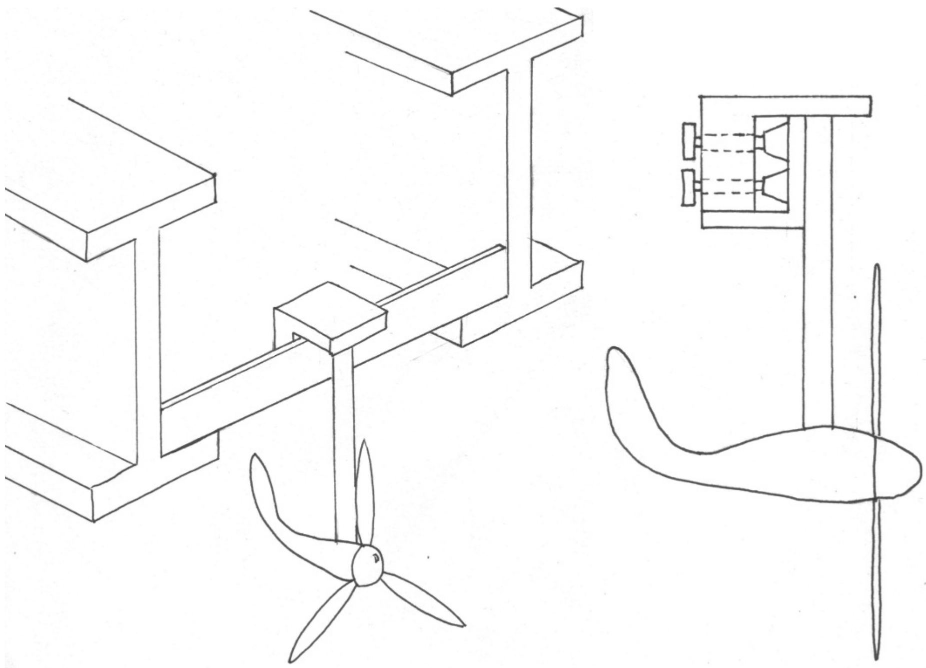

Figure 18: Fourth attachment system with an isometric view (left) and side view (right)

5. ROAD AHEAD AND CONCLUSION

A methodology to select and design attachment systems that are novel, feasible, and capable of meeting system requirements is presented. An empirical study was conducted examining various products, patents, and biological examples which helped formulate and organize the list of attachment principles. A case study demonstrating the usefulness of the methodology and selected TRIZ principles in generating design concepts within the context of a bridge mounted wind harvester was presented.

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. It would be beneficial to utilize the methodology within the context of other design problems to further refine the attachment principles and produce a more holistic methodology. The ultimate goal is that this methodology will become a useful tool for designers. A user survey or questionnaire that identifies the top three attachment principles based on guided questions might be one approach for formalizing the tool. Ideally this tool will automate design and help inspire those involved in creating innovative attachment systems.

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