**Proceedings of IDETC/CIE 2006**
**ASME 2006 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference**
**Philadelphia, PA, September 10-13, 2006**

**DETC2006-99575**

# INNOVATIONS IN DESIGN THROUGH TRANSFORMATION: A FUNDAMENTAL STUDY OF tRaNsFoRmAtIoN PRINCIPLES

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## Abstract

The act of creating a new product, system or process is an innovation: the result of excogitation, study and experimentation. It's an inductive and/or deductive process. The former is a process of studying systems that exist, for example, in nature, patents and products, and inducing from these system behavior and elemental features for innovating novel products. The latter is a process of deducing such aspects from hypothetical concepts and situations where systems or products could exist. Using a combined inductive and deductive approach, this paper reports on a methodology for the creation of innovative products with a much broader functional repertoire than traditional designs. This breed of innovative products possesses a broader functional repertoire by transforming into different configurations. Current design theory lacks a systematic methodology for the creation of products that have the ability to transform. This paper identifies analogies in nature, patents and products along with hypothesizing the existence of such products in different environments and situations. Transformation Design Principles are extracted by studying key design features and functional elements that make up a transforming product. These principles are listed, defined and categorized according to their roles in generic transformations. The principles and categorizations are then validated and applied to conceptualize a transforming product as an example of an innovative design.

**KEYWORDS:** Design Principles; Transformational Design; Design Transformation Theory; Inductive Research; Deductive Research

## 1.0 INTRODUCTION

### 1.1 Motivation

To understand the motivation for this research, consider the following questions:

- What are the benefits of *transforming* a product versus *creating* a new product with a single function focus?
- How is *transformation* defined?
- How can we achieve product transformation?
- Can we create design methodologies that can facilitate the development of transforming products?

*What are the benefits of transforming a product versus creating a new product with a single function focus?*

Most products have a single primary function along with a number of subordinate secondary functions. For example a common chair will be used primarily to sit, but it can also be used as a step ladder having only one step or a weight of some sort. Chairs that become step ladders exist and achieve both functions by transforming between a chair configuration and a stepping ladder. Figure 1 shows this example as well as other transforming devices.

An electric leaf blower is another good example of a product that reconfigures to become a vacuum cleaner in another configuration. A hand sander, portable jig saw and hand drill perform different functions but can be designed into a single tool with different modules [1]. These are a few examples of products that have been designed for transformation, but retain their primary functions within their product domain, identified in Figure 1 by a dotted/dashed circle. The domain of a product (tagged with a common color bubble in the figure) includes products of similar need, design embodiment and functionality defined by their use and environment. For example a leaf blower and a vacuum cleaner are in the same product domain as their primary function is to

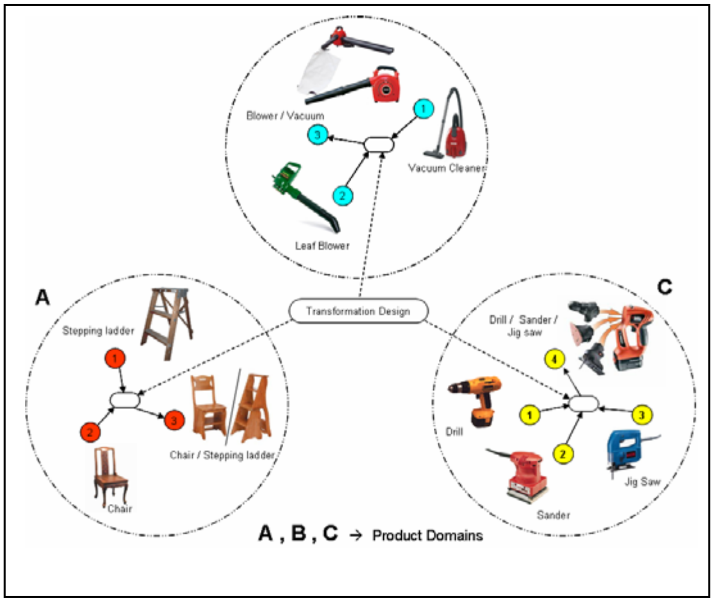



FIGURE 1. TRANSFORMATION WITHIN PRODUCT DOMAIN [2–11]

satisfy the need of removing unwanted objects. Similarly a chair and a step ladder have structurally related functions, so they are in the same product domain. An example of a transforming chair crossing a product domain would be if the chair transformed itself to a magnetic levitating device for elevating the user to a new height instead of transforming into a step ladder. A single product that can transform to perform multiple functions can have an increased task profile with increased efficiency compared to several single-function products or single form multi-function products. Functions that a single transforming product can perform need not be related nor require the same basic form. This characteristic is not generally true of single-state multifunction products.

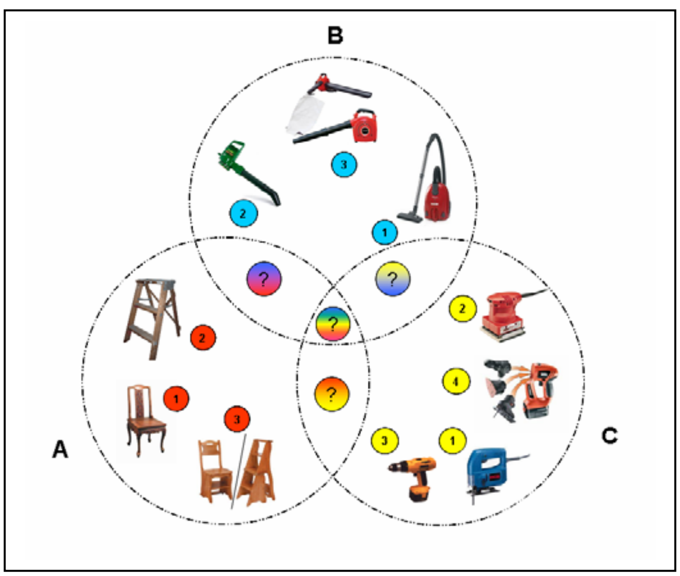



FIGURE 2. OPPORTUNITIES FOR TRANSFORMING PRODUCTS [2-11]

Transforming products can bridge the functionality gap between products by crossing into other product domains (for example: a vacuum cleaner that transforms into a chair), energy domains (for example: manual drill transforming into a power drill, both required in different conditions), new and old technology (for example: a white board transforming into a screen displaying and storing what's written on the white board), etc. Figure 2 gives a clear idea of where opportunities for transforming products exist. With transformation of products, we can increase a product's utility by expanding its functional domain. For example the analogy of a Venn diagram in Figure 2 depicts that transforming product possibilities represented by **A∩B** perform similar functions, if not all, as found in the product domain of **A** and **B**. These transforming products now exist in an expanded product domain of **AUB** possibilities**.** Figure 2 also shows other design possibilities for product transformation identified by **B∩C**, **C∩A** and **A∩B∩C**.

Transforming products hold many advantages over single-state designs. The primary advantage is that the same device is able to perform multiple functions. By creating a transforming product that performs tasks usually requiring multiple devices, increases in efficiency can be realized throughout a wide range of customer needs. For example:

- Cost may be reduced since labor and material is typically less for a single device.
- Benefits may be achieved in weight-sensitive applications
- Benefits may be achieved by having one system that can accomplish the functions that may previously have been done by separate products.
- Transformational design could be a solution for designing products that serve multiple functions involving conflicting parameters, which affect these functions, to be separated in time.
- Scheduling and logistical issues may be simplified by using multifunctional devices.
- Certain transforming devices may perform functions between states that are not possible in single-state products.
- Deployment time may be reduced for many designs.
- The whole is greater than the sum of its individual parts. A single design that can transform to perform multiple functions may have an increased functional repertoire compared to several single-state devices.
- The functions that a single product can perform need not be related or require the same structural layout, as with other single-state multifunctional devices.

Transformation does, however, carry potential detriments to the design process. One of the goals of a design methodology is to reduce or eliminate these disadvantages. The most prominent issues are:

- Transformational design requires significantly more initial time to develop successful products. Due to the complexity of transformers in general, their design produces unique technical issues that must be overcome. The additional cost associated with their design must be weighed against their functional benefits.
- The inclusion of transforming elements can negatively impact certain parameters of a product, such as its weight

or volume. In order to accommodate the elements necessary for transformation, tradeoffs are inevitable. Again, these must be considered in light of the added functions provided by reconfigurable devices.
- As with any multi-use product, certain functions may be impacted negatively by the inclusion of others. Because components in a multi-state product are frequently shared, their design is governed by two separate sets of objectives, which may or may not be aligned. This can cause conflicts in the design process that can decrease the efficiency of the product in any given state.

These potential problems posed by the design of transforming products must be addressed in the creation of a formal design methodology. To facilitate the creation of transforming products, as a first step we have to understand what principles govern transformation.

## 1.2 Objective

This paper reports on research in design for transformation by: identifying and studying fundamental principles of transformation found in nature, products and patents, hypothesizing transforming principles by questioning ways of achieving transformation, and creating a methodology to develop transforming products. Such a methodology will provide designers with a set of transformation design principles and a process by which they can be applied.

## 2.0 RESEARCH APPROACH

The approach of this research is to employ both induction and deduction to address the research questions. This approach is shown in Figure 3. The combined approach is used to derive heuristic rules called "principles" for transformation from examples found in nature, existing products and patents that exhibit transformation (inductive approach) and from situations or scenarios that would require the need for transforming a device (deductive approach).

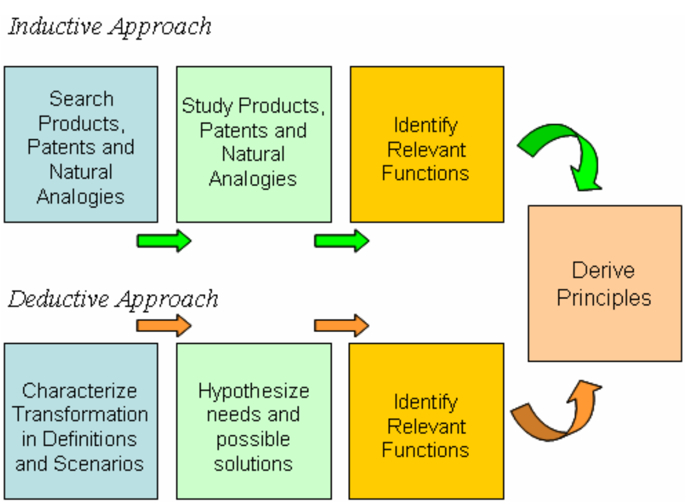



FIGURE 3: RESEARCH STUDY APPROACH

Using the combined inductive/deductive approach, we developed a research study process flowchart that is divided into two sections, where one section follows the inductive approach and the other section the deductive approach. This research flow is shown in Figure 4 and explained in the next section.

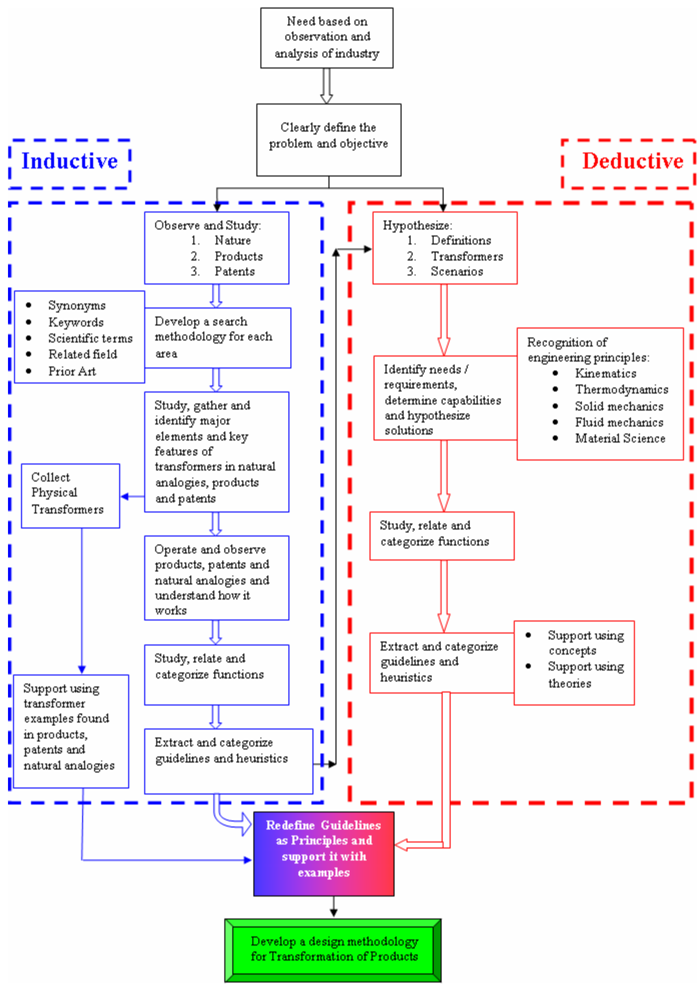



FIGURE 4. RESEARCH STUDY PROCESS

## 2.1 Inductive Approach

We use an inductive approach to gather and study an extensive repertoire of transforming analogies from nature, existing products and patents. This process represents an empirical study. The first step to such an approach is to search for examples of transforming devices in each of the three categories. We have employed a wide variety of search methodologies and continue to refine our search process. The complete details of the search methodology will be the subject of future publications.

### 2.1.1 Natural Analogies

The search for natural analogies is depicted in Figure 5. Synonyms for "transform" are listed and used as keywords to search the appropriate literature. With the results produced from this search, a literature review, and interviews with biologists, the list is refined into scientific terms like structural adaptability, functional morphology, phenotypic plasticity, etc. This result is iterated with further literature searches to expand the list of natural analogies.

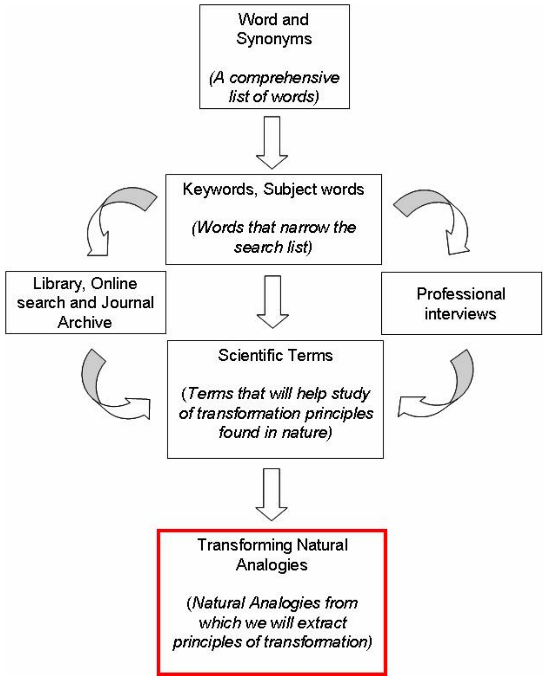



FIGURE 5. SEARCH METHODOLOGY FOR NATURAL ANALOGIES THAT TRANSFORM

### 2.1.2 Patent

Patents are searched using the following methodology, (shown in Figure 6): a list of keywords is generated using "transform" as a base and exploring synonyms that are likely to appear in patent literature. Words related to transforming devices such as "multifunctional" and "integrated" are also included. A list of limiting words is generated to eliminate patents that relate to other types of transformation that are not considered as part of this research. These include excluding words such as "chemical," "electrical," and "data" that should eliminate a patent from consideration. A list of words such as "tool," "machine," and "device," are developed to be included in the search to allow us to focus on mechanical transformations. Analysis is performed on each of the limiting words to determine which words most effectively focus the search on desirable patents. This search approach is accomplished by performing patent searches on each combination of keywords and limiting words and comparing the quantity of the results. The most effective limiting words are used in the final search. Patent searches are then performed on the US Patent and Trademark Office website [12], the European Patent Office website [13], and Free Patents Online [14] for the most promising combination of keywords and limiting words. Additional patents from the same inventors and assignees are examined as well as those that are referenced by other relevant patents.

### 2.1.3 Products

Transforming products are found using the methodology shown in Figure 7. A list of keywords is generated in a similar method to that used in the patent and natural analogy research. Additional keywords are found by using the descriptions of transformers found in the patent and natural analogy results. When a transforming product was found, additional searches were performed to find related products and technology.

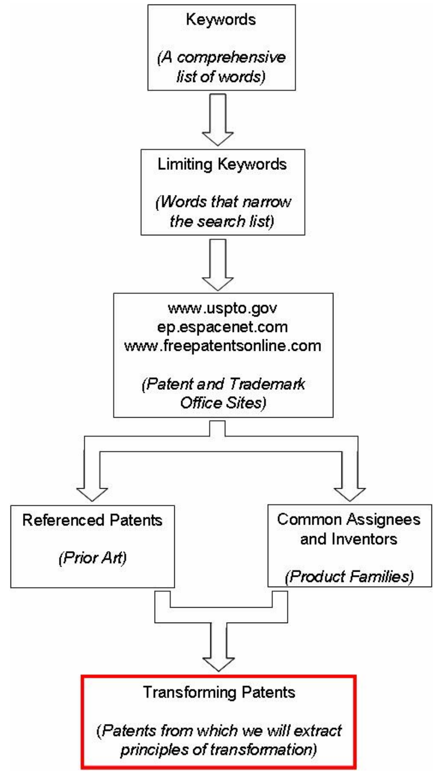



FIGURE 6. SEARCH METHODOLOGY FOR PATENTED DEVICES THAT INVOLVE TRANSFORMATION

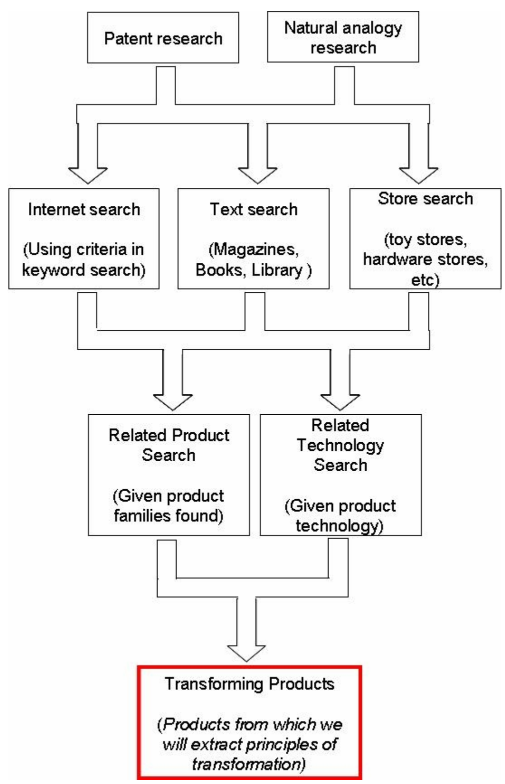



FIGURE 7. PRODUCT SEARCH METHODOLOGY

### 2.2 Deductive Research Approach

Whereas an inductive research approach takes advantage of the existing body of work, a deductive approach tries to expand the domain of transforming principles through the combined use of hypothetical definitions, theoretical approaches and hypothetical scenarios. As graphically explained in Figure 8, the objective is to derive a suite of transformational principles by a progression of mental gymnastics beginning with hypothetical definitions and scenarios, imagining embodiments of these scenarios, identifying associated functions and using these results to derive principles. The development of hypothetical definitions and scenarios is aided by identifying common capabilities that transformational products might exhibit. Creation of solutions or embodiments is facilitated by recognition of the engineering principles involved (kinematics, thermodynamics, solid or fluid mechanics etc.) Functions and relevant aspects that facilitate transformation are identified from the list of possible solutions where the functions lead to the deduction of principles and/or guidelines that aid in the design of transforming devices.

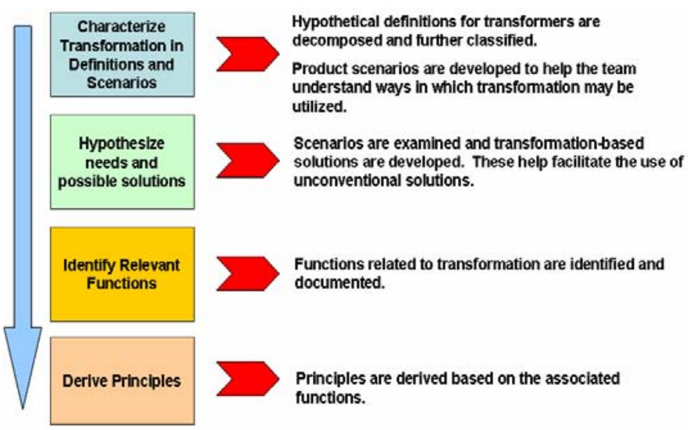



FIGURE 8. DEDUCTIVE RESEARCH APPROACH

### 3.0 PRINCIPLE EXTRACTION

Through the search methodologies and study of features, mechanisms, and utility. we identified qualities and functions that characterize devices that transform and hence establish principles and attributes that we call “facilitators” that lead to a transforming device.

### 3.1 Inductive Principle Extraction

The inductive research process of principle extraction makes use of studying existing products, patents and natural analogies. Major elements and key features of the product or invention at a systems level and/or parts level were identified for functionality, interaction and physical state as related to transformation. The different transformation types were listed and grouped as heuristics that bring about transformation (principles) or that facilitate transformation (facilitator). “Principles” describe what causes the transformation while “Facilitators” describe what make the transformation function correctly.

### 3.2 Deductive Principle Extraction

From the deductive perspective of principle extraction, transformation principles and facilitators are applied or incorporated into the design architect of a transforming product. This is done to expand either the solution set of product capabilities, the capabilities themselves or both. These hypotheses lead us to identify new or repeated principles or facilitators (from inductive principle extraction).

### 3.3 Transformation Principles and Facilitators Categorization

Figure 9 shows a preliminary list of Transformation Facilitators.

| | |
|---|---|
| Interchangeable transmissions | Use multiple transmissions to produce different motions |
| Common core structure | Compose devices with a core structure that remains the same, while the periphery reconfigures to alter the function of the device |
| Modularity | Localize related functions utilizing common signal, material, and force flows into subsystems (modules) which are easily integrated into the device and may be interchangeable |
| Generic Connections | Employ internal or external connections (structural, power) that can be used by different modules to perform different functions or perform the same function in a different way |
| Composite | Form a single part from two or more parts with distinct functionality |
| Fuse/Divide | Make single functional device become two or more devices, at least one of which has its own distinct functionality defined by the state of the transformer or vice versa |
| Shared Power Transmission | Transmit power from a common source to perform different functions in different configurations |
| Segmentation | Divide single contiguous part into two or more parts |
| Conform with structural interface | Statically or dynamically constrain the motion of a component using structural interfaces |
| Function Sharing | Make a single part perform two or more discrete functions throughout the state of the transformer |
| Function Shifting | Make a single part perform two or more discrete functions, defined by the state of the transformer |
| Shelling | Embed functional element in a device which performs a different function |
| Expose/Cover | Expose/Cover a new surface to alter functionality |
| Flip | Perform separate functions based on orientation of the object |
| Expand/Collapse | Change physical dimensions of object along and axis, in a plane, or in three dimensional space |
| Enclosure | Manipulate object in two or three dimensions in order to enclose a three dimensional space |
| Material Flexibility | Change object dimensions with change in boundary conditions |
| Nesting | Place an object inside another object wholly or partially wherein the internal geometry of the containing object is similar to the external geometry of the contained object |
| Furcation | Change between two or more discrete stable states determined by boundary conditions |

FIGURE 9. PRELIMINARY LIST OF TRANSFORMATION FACILITATORS

To determine Transformation Principles from this list, the facilitators were studied and grouped. The steps involved in the process are described below (see Figure 10 for graphical depiction):

*Step 1*: The facilitators were grouped on the basis of identifying major elements and key features of the existing and/or hypothesized product at a systems level and/or parts level. For example *Interchangeable Transmissions, Common Core Structure, Modularity, Generic Connections,* and *Shared Power Transmission* were grouped together.

Step 2: To create a visual representation, the facilitators that were grouped were color coded; each group of facilitators was

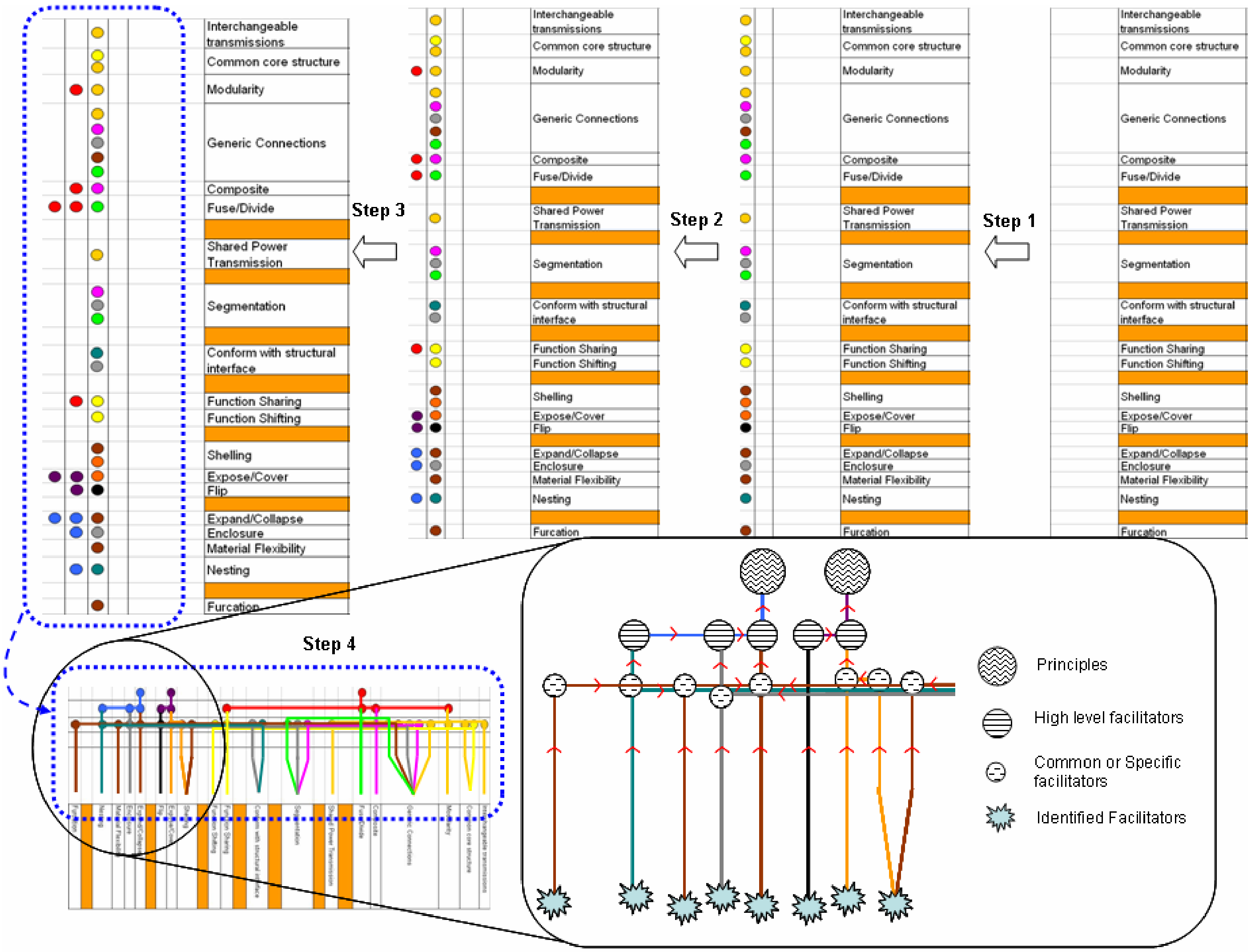



FIGURE 10. TRANSFORMATION PRINCIPLES AND FACILITATORS CATEGORIZATION WITH BOTTOM TO TOP MAPPING OF FACILITATORS TO PRINCIPLES

assigned a different color. This process of tagging groups with a common color helped to iterate the formation of these groups and identify that these groups of facilitators could cross the initial raw distinctions by either including common facilitators or incorporating another group of facilitators as a sub group. For example *Generic Connections* is found in quite a few groups as a common facilitator; *Common Core Structure* is also found to be common facilitator for *Modularity* and *Function Sharing - Function Shift (Function Shift* came under *Function Sharing),* and *Furcation* was identified as a facilitator grouped only under *Expand/Collapse* [15, 16].

*Step 3*: The next step was to identify super groups, if any, to these facilitator sub groups. A different color was tagged next to the facilitator that fully captured the common functionality, interaction and physical states as described by the transformation facilitators. For example this process resulted in a super group involving *Modularity, Composite, Fuse/Divide* and *Function Sharing.*

*Step 4*: With higher level facilitators, *Modularity, Composite* and *Function Sharing* physically being embodied by *Fuse/Divide*, this process resulted in all the transformation facilitators in the mechanical domain being categorized by three fundamental transformation principles: *"Expand/Collapse"*, *"Expose/Cover"* and *"Fuse/Divide"*. Figure 10 shows the mapping of the transforming facilitators leading to transformation principles, from bottom to top.

## 4.0 DEFINITIONS AND PRINCIPLE DESCRIPTION

Based on the facilitator extraction process, we arrive at the following formal definitions:

***Transformation Principle***

A Transformation Principle is a generalized directive to bring about a certain type of mechanical transformation. A transformation principle is a guideline that, when embodied, singly creates a transformation.

***Transformation Facilitators***

A Transformation Facilitator is a design architect that helps or aids in creating mechanical transformation. Transformation

Facilitators aid in the design for transformation but their implementation does not create transformation singly

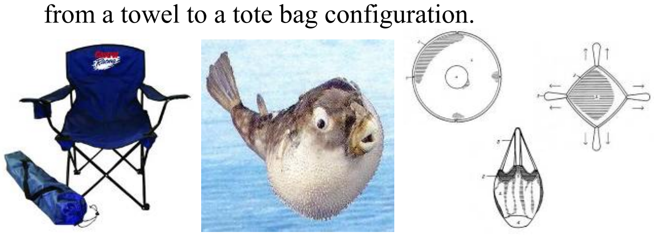
### 4.1 Transformation Principles

For consistency, a common form of writing the principles and facilitators is desired. This means the development of a common lexicon to achieve an equivalent semantic level for each principle and facilitator. The lexicon is similar to the design principles stated in The Theory of Inventive Problem Solving (TIPS or TRIZ), developed by Genrikh S. Altshuller in the former U.S.S.R., beginning in the late 1940s [17, 18, 19, 1].

Through our research approach as described in the 4 step process given above, we believe that there are three fundamental transformation principles, *"Expand/Collapse", "Expose/Cover" and "Fuse/Divide"*, which fully represent transformation potential in the mechanical domain. Subordinate to these three principles there are transformation facilitators. The hierarchical relationship between principle and facilitator exists because principles describe what causes transformation while facilitators describe what make the transformation function correctly.

We list the principles and facilitators found in the mechanical domain in Figure 11. The list graphically shows the three transformation principles on the left with their facilitators on the right. Common facilitators are highlighted. The facilitators themselves are being further explored and decomposed to have a clear list encapsulating all the possibilities for a transformational design in the mechanical domain. For example the *Expand/Collapse* principle, by definition, encompasses the applicability of some facilitators, but the principle can itself be further divided/branched into possible physical descriptions like *Wrap/Fold*, *Telescope/Slide*, etc. (shown by a dotted callout box) which an expanding/collapsing structure can embody.

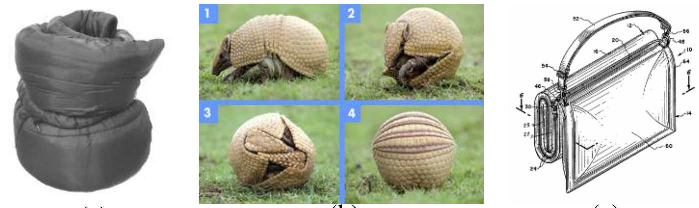
- *Expand/Collapse – Change physical dimensions of an object to bring about an increase/decrease in occupied volume primarily along an axis, in a plane or in three dimensions.* Collapsible or deployable structures are capable of automatically varying their shape from a compact, packaged configuration to an expanded, operational configuration. In Figure12: (a) the portable sports chair expands for sitting and collapses for storage or portability; (b) the puffer fish expands its body to ward of and escape predators; and (c) the bag in this patent expands from a towel to a tote bag configuration.



(a) (b) (c)

FIGURE 12. EXAMPLES "EXPAND/COLLAPSE" [20-22]

- *Expand/Collapse: Wrap/Fold – Wrap or fold to create different functions in different configurations.* Such reconfigurability makes use of properties like material flexibility and parts connected by movable joints. In Figure 13: (a) a sleeping bag rolls for storage; (b) an armadillo can roll up to protect itself; (c) the bag unfolds to become a blanket



(a) (b) (c)

FIGURE 13. EXAMPLES "WRAP/FOLD" [23-25]

- *Expose/Cover – Expose a new surface to alter functionality.* This principle is a directive for changing the surface of a device or its parts so as to alter the primary function of the device. This alteration can be brought about by different type of part to part interaction of the device and/or the form of the device itself. In Figure 14: (a) the chair rotates and exposes new surfaces to become a step ladder; (b) the Day-Blooming Water Lily opens during the day to expose its interior, and closes at night; (c) the keyboard in this patent folds out to reveal the operational surface.

(a) (b) (c)

FIGURE 14. EXAMPLES "EXPOSE" [6, 26, 27]

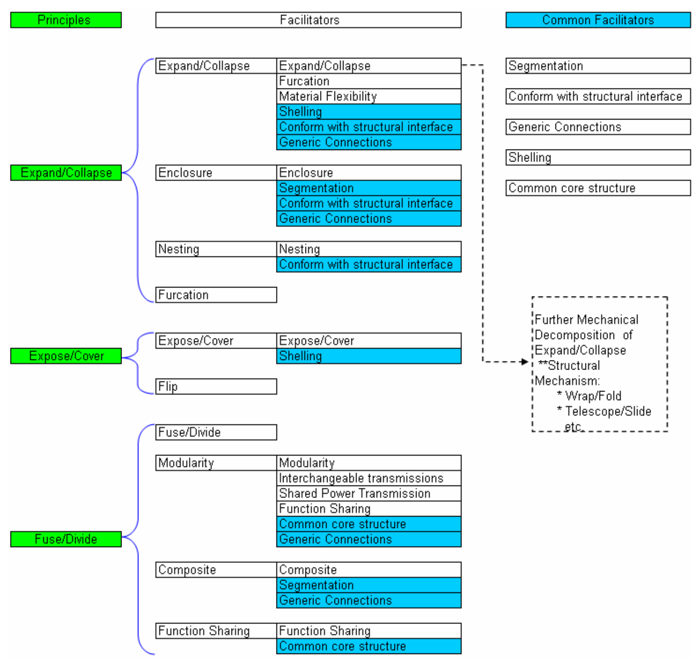
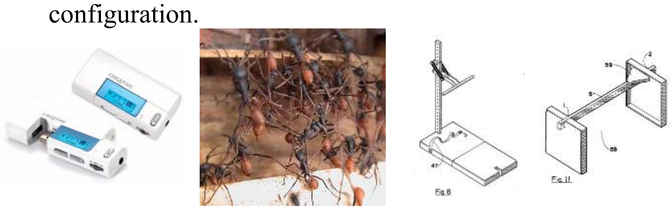



FIGURE 11. LIST OF PRINCIPLES AND FACILITATORS

- *Fuse/Divide - Make single functional device become two or more devices, at least one of which has its own distinct* *functionality defined by the state of the transformer, or vice versa*. A functional device divides into two or more parts where at least one of the parts has a distinct primary function. Two or more parts with distinct or similar primary functions can fuse/join to form a new device with a distinct primary function. In Figure 15: (a) the product shown is an audio player which also functions as a USB flash drive or a memory stick. It connects to a power source module making the audio player portable; (b) Army ants join their bodies to form a bridge for the rest of the colony; (c) the patented device shown has its parts divide from functioning as a platform for human interface to form two separate supports for the second exercise equipment configuration.



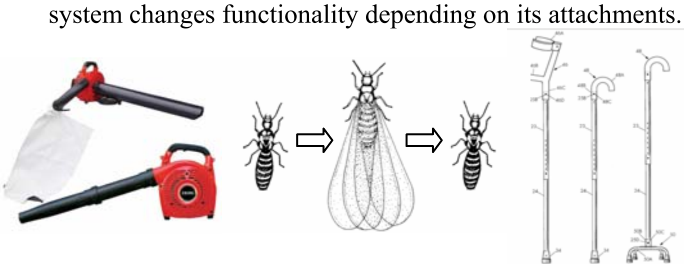
(a) (b) (c)

FIGURE 15. EXAMPLES “FUSE/DIVIDE” [28-30]

### 4.2. Transformation Facilitators

While singly embodying a Transformation Principle can create a transforming product, Transformation Facilitators aid in the design of transformers but their implementation does not create transformation alone. These Transformation Facilitators are:

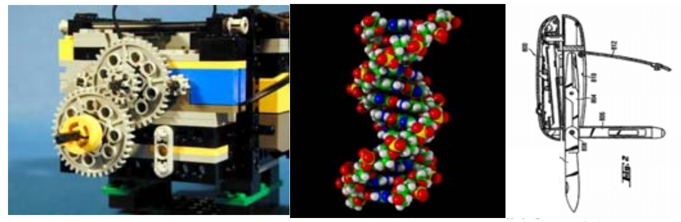
- *Common Core Structure - Compose devices with a core structure that remains the same, while the periphery reconfigures to alter the function of the device.* In essence a reconfigurable device can consist of a core structure that basically is the main support structure that allows for aligning/positioning different peripheral parts or systems. In Figure 16: (a) the leaf blower’s working organ shown here remains the same while the usable implements change the device operation from a blower to a vacuum; (b) the reproductive termite begins life as a crawling insect, then grows wings to leave the colony, and sheds its wings to take the roll of king or queen of a new colony; (c) the cane system changes functionality depending on its attachments.



(a) (b) (c)

FIGURE 16. EXAMPLES “COMMON CORE STRUCTURE” [2, 31, 32]

- *Composite – Form a single part from two or more parts with distinct functionality*. Here the parts that form the composite structure don’t functional individually, but become functional when arranged together. In Figure 17: (a) LEGO® parts shown in the drive system consist primarily of a set of splined shafts (black) and mounted gears (grey). The individual gears and the splined shafts alone don’t perform any function; (b) DNA changes its function based on the specific sequencing of nucleotides; (c) the shape of the blunt edge of a utility knife, in this patent, forms a handle out of its cutting utensils when they are not in use.



(a) (b) (c)

FIGURE 17. EXAMPLES “COMPOSITE” [33-35]

- *Conform with Structural Interfaces - Statically or dynamically constrain the motion of a component using structural interfaces.* Parts or devices structurally conform with other parts or devices to aid in the transformation of the part or device to produce distinct functionality. In Figure 18: (a) flip phones maintain their open position by constraining the motion of the headset section against a structural interface on the base; (b) the kangaroo uses its tail as a structural member that interfaces with the terrain to provide more support while standing; (c) the container uses self-locking structural interfaces to define its final shape.

(a) (b) (c)

FIGURE 18. EXAMPLES “CONFORM WITH STRUCTURAL INTERFACES” [36-38]

- *Flip - Perform different functions based on the orientation of the object.* This facilitator implies re-orienting an object, where the object now has a different interacting surface to facilitate a different functionality. In Figure 19: (a) the hand held light is flipped to expose its solar cell array and interface with the handle; (b) an otter’s belly, when floating upside down, functions as a horizontal support surface for carrying young or preparing food; and (c) the patent shown functions as a stapler on one end and when flipped upside down the opposite end functions as a hole punch.

(a) (b) (c)

FIGURE 19. EXAMPLES “FLIP” [39, 40, 35]

- *Function Sharing*: *Perform two or more discrete functions.* The transforming device consists of parts that have two or more functions defined by the state of the transforming device or throughout the state of the transforming device. In essence the part is multi functional in a configuration (function sharing) or a part of the device performs a primary function in one configuration, but performs a different primary function in another state of the device (function shifting). In Figure 20: (a) the rims of the rear wheels of this amphibious toy car become propellers in an alternative configuration of the wheels; (b) while resting, the pattern on this butterfly's wings mimics the eyes of a larger animal to ward off potential predators; (c) the dumbbells of this patented exercise equipment function as legs in an alternative configuration, an example of function shifting.


(a) (b) (c)

FIGURE 20. EXAMPLES "FUNCTION SHARING" [41-43]

- *Furcation – Change between two or more discreet stable states determined by the boundary conditions*. A transforming product is designed with multiple stable states and the transition between these states is defined by a set of boundary conditions imposed upon it. In Figure 21: (a) the common slap bracelet toy is an example of a bi-stable structure that is stable in its extension state until part of its cross-section is flattened, at which time it collapses to a lower-energy coiled state; (b) a Venus fly trap snaps it leaves shut in about one tenth of a second by reversing the curvature of its leaves releasing stored energy.; and (c) an umbrella is a bifurcating device with two stable states – open and closed.


(a) (b) (c)

FIGURE 21. EXAMPLES "FURCATION" [44-46]

- *Generic Connections - Employ internal or external connections (structural, power) that can be used by different modules to perform different functions or perform the same function in a different way.* Basic common interconnections between parts of a device or between devices facilitate the transformation of a device or a system having a distinct functionality. In Figure 22: (a) the poles and connecters in this product form different structures using quick connections; (b) identical synaptic connections between two brain cells can result in different end effects, depending on the different connection configurations; (c) the bars and nodes of this patent can be reconfigured for a variety of structures.

(a) (b) (c)

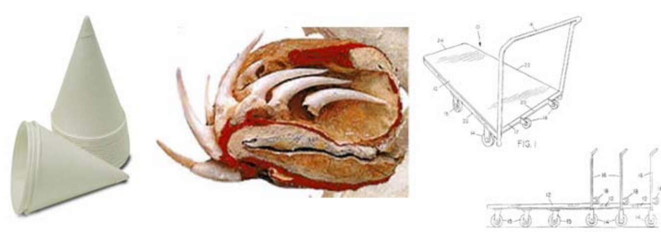
FIGURE 22. EXAMPLES "GENERIC CONNECTIONS" [47-49]

- *Modularity - Localize related functions into product modules.* Product modules are distinct building blocks that combine to form machines, assemblies or components that accomplish an overall function [50, 1]. In Figure 23: (a) this tool set changes functionality as different modules are attached; (b) the hermit crab can transform its outward appearance by changing between different shells as needed where the shell primarily acts as protection; (c) the legs, head, and body of this robot are modular.

(a) (b) (c)

FIGURE 23. EXAMPLES "MODULARITY" [51-53]

- *Nesting - Place an object inside another object wholly or partially wherein the internal geometry of the containing object is similar to the external geometry of the contained object.* One object is placed inside the other or one object passes through a cavity or interfaces with a cavity in another object [18, 1]. In figures 24: (a) water fountain cones nest for easier storage; (b) sharks have nested sets of teeth so they never run out of teeth. If one is lost, another spins forward from the rows and rows of backup teeth; (c) these utility carts nest so that several can be stored is a smaller space




(a) (b) (c)

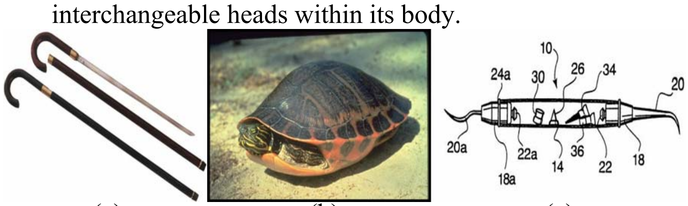
FIGURE 24. EXAMPLES "NESTING" [54-56]

- *Shared power transmission – Transmit power from a common source to perform different functions in different configurations.* Power is transmitted from a single power source (e.g., an engine, motor) to perform separate tasks in different states. In Figure 25: (a) the Bell Boeing MV-22 Osprey™ uses a common engine for vertical and horizontal movement; (b) bats use their fore limbs when not in flight to move on the ground and as wings for flight; and (c) the transformation from a wheel to a track system in this patent also adds a new secondary function of acting as a suspension.

(a) (b) (c)

FIGURE 25. EXAMPLES “SHARED POWER TRANSMISSION” [57-59]

- *Shelling – Embed functional element in a device which performs a different function.* Shell or cover a component or part(s) of a component inside itself, with or within another component. In Figure 26: (a) a blade is embedded within the shaft of the cane; (b) turtles hide within their hard shells to protect themselves from predators; (c) the patent shows a modular instrument that hides its interchangeable heads within its body.




(a) (b) (c)

FIGURE 26: EXAMPLES “SHELLING” [60-62]

## 5.0 RESEARCH RESULTS

The primary results of the research include:

- A list and definitions of Transformation Principles and Facilitators
- Validation of this list
- Application of the principles and facilitators

### 5.1 List and Definition of Transformation Design Principles and Facilitators

The design principles and facilitators documented in Section 4 are heuristic rules which create high level concepts that propose inventive solutions for designing a transforming product. The results are summarized in Figure 27.

### 5.2 Validation

It is necessary to determine what number of products, patents and natural analogies is sufficient to capture the overwhelming majority of transformation design principles and facilitators. To determine this sufficiency condition, data was compiled for the number of distinct principles that each product, patent and natural analogy revealed. We present the sufficiency condition for patents in Figure 28, where, here again, the focus is on the mechanical domain. Two lines are plotted from the data, one displaying the number of new facilitators or potential principles that each patent exposed, and the other tracking the cumulative total of principles. These two plots are superimposed on the same chart.

The plots clearly show that the majority of principles are extracted in the first half of patents analyzed. Analysis of the

| | | |
|---|---|---|
| Principles | Expand/Collapse | Change physical dimensions of object along and axis, in a plane, or in three dimensional space |
| | Expose/Cover | Expose/Cover a new surface to alter functionality |
| | Fuse/Divide | Make single functional device become two or more devices, at least one of which has its own distinct functionality defined by the state of the transformer or vice versa |
| Facilitators | Common core structure | Compose devices with a core structure that remains the same, while the periphery reconfigures to alter the function of the device |
| | Composite | Form a single part from two or more parts with distinct functionality |
| | Conform with Structural Interfaces | Statically or dynamically constrain the motion of a component using structural interfaces |
| | Enclosure | Manipulate object in two or three dimensions in order to enclose a three dimensional space |
| | Flip | Perform separate functions based on orientation of the object |
| | Function Sharing | Perform two or more discrete functions |
| | Furcation | Change between two or more discrete stable states determined by boundary conditions |
| | Generic Connections | Employ internal or external connections (structural, power) that can be used by different modules to perform different functions or perform the same function in a different way |
| | Interchangeable transmissions | Use multiple transmissions to produce different motions |
| | Material Flexibility | Change object dimensions with change in boundary conditions |
| | Modularity | Localize related functions utilizing common signal, material, and force flows into subsystems (modules) which are easily integrated into the device and may be interchangeable |
| | Nesting | Place an object inside another object wholly or partially wherein the internal geometry of the containing object is similar to the external geometry of the contained object |
| | Segmentation | Divide single contiguous part into two or more parts |
| | Shared Power Transmission | Transmit power from a common source to perform different functions in different configurations |
| | Shelling | Embed functional element in a device which performs a different function |

FIGURE 27. LIST AND DEFINITIONS OF TRANSFORMATION DESIGN PRINCIPLES AND FACILITATORS

first eight patents alone yielded 17 of the 19 Transformation Principles and Facilitators (a verification of the search procedure developed for patents). If this trend holds true in general, it can be assumed that, while it is very possible that not all principles were discovered with an analysis of only 41

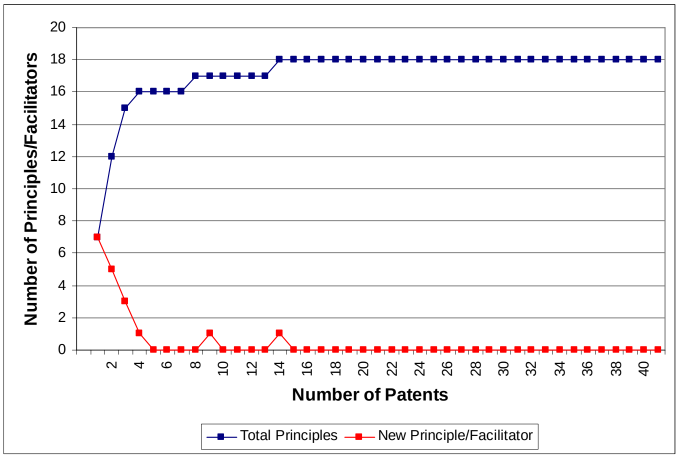



FIGURE 28. NUMBER OF PRINCIPLES/FACILITATORS VS. NUMBER OF PATENTS ANALYZED

patents, a high percentage of them were. This validation is a continuing process, where, at the limit, with a large repertoire of products, patents and natural analogies, the number of principles/facilitators flattens (or becomes asymptotic) versus the number of patents/products/natural analogies analyzed. A similar validation may be generated and is being continued for natural analogies and products.

### 5.3 Application in Design for Transformation:

Given the developing theory of design for transformation, transformation principles and facilitators we developed a list of potential transformers that such a design theory could embody. Some of these potential transforming products are listed in Figure 29. This list of example transformers are not generated strictly from the transformational design methodology, which is being developed

The research powered and invigorated our interest of transforming a concept that combines multiple principles and facilitators to transform. An idea, which the research team found to have an attractive application, consists of a motorcycle that transforms into an all terrain vehicle (ATV). Figure 30, helps to illustrate the need for such a transformer. A motorcycle is more maneuverable, aerodynamic and smaller than an ATV but is unfit for all terrains, less stable at low speeds, not suited for reverse motion and transports less material as opposed to an ATV. For example a motorcycle would be unfit for slowly crawling on rough terrain as it is balanced by only two wheels, but it is required when the need is for maneuverability and smaller occupied space. The transformer can satisfy the combined needs and functionality of a motorcycle and an ATV. We used our theory of transformation, which is a collection of Transformation Principles and Transformation Facilitators to develop a concept of a transformer that transforms from a 2 wheel configuration into a 4 wheel configuration, Figure 31.

1. Sail Boat ←→ Tent ← → Table ← → Chair ←→ Hammock ←→ Trampoline
2. Bicycle ← → Tent ← → Chair ←→ Table
3. Window Blinds ←→ Fan
4. Drill ← → Vacuum Cleaner
5. Headphones ← → Portable Speakers
6. Motorcycle ← → All Terrain Vehicle
7. Skateboard ← → In-line skates
8. All Terrain Vehicle ← → Jetski
9. Backpack ← → Jacket
10. Toaster ← → Blender
11. Chairs ←→ Table ←→ Sofa ← → Bed
12. Football ← → Soccer ball
13. Base Ball bat ← → Golf stick
14. Guitar ← → Artists Easel
15. Bicycle ← → Exercise Machine
16. Back yard ← → Swimming pool
17. Ski ← → Snowboard
18. Surf Board ← → Car's Roof
19. Pen ←→ Umbrella ← → Walking stick
20. Car ← → Tent ←→ Picnic Table
21. Washing Machine ← → Blender ← → Microwave Oven
22. Control Pad (game) ← → Gun (game)
23. Gaming Console ← → Board game
24. Air Craft Carrier ← → Submarine
25. Broom ←→ Vacuum Cleaner ← → Shoe shiner
26. Pen ←→ Cup ← → Umbrella
27. Flash light body ←→ Table lamp ←→ Personal fan ← → Make up kit
28. Hat ←→ Umbrella ←→ Sun glasses
29. Automobile ←→ Kiosk ← → Boat
30. Rifle ←→ Guitar ←→ Umbrella
31. Dog bowl ←→ Dog leash

FIGURE 29. LIST OF TRANSFORMER IDEAS

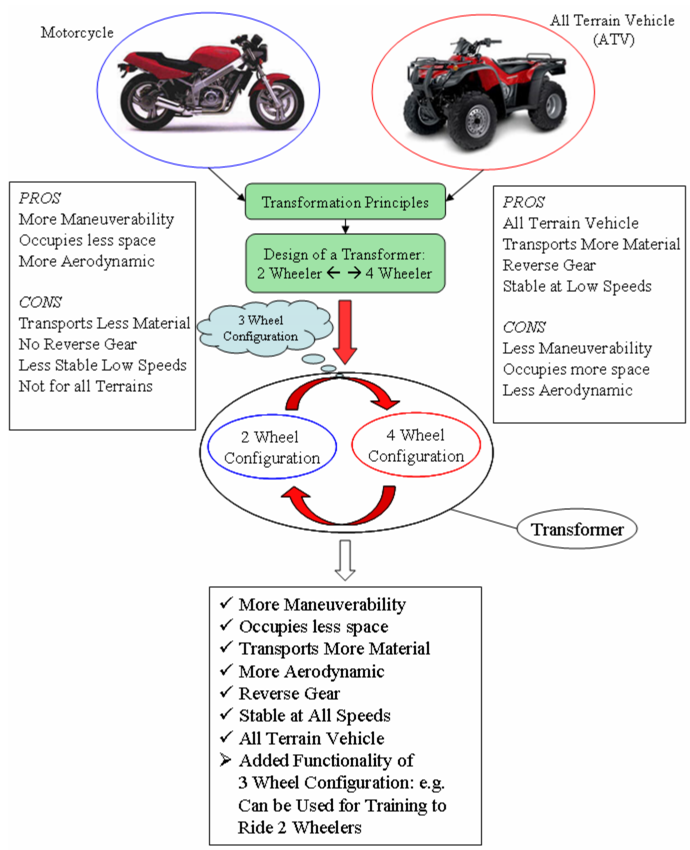



FIGURE 30. COMPARISON OF A MOTORCYCLE AND AN ATV [63, 64]

The design process started with identifying the most complex common sub assemblies, for example the wheels. The states of the sub assemblies were studied, and principles were applied to bring transformation between the states. For example transformation (Figure 31, 32 and 33) from a motorcycle to an ATV incorporates the following Transformation Principles and Facilitators:

- Each wheel divides into two wheels: *Fuse/Divide*.
- Body shell and structure are made of different parts with a collapsing structure that facilitates the operation of transforming from the motorcycle to the all terrain vehicle body: *Expand/Collapse* with *Fuse/Divide, Conform With Structural Interface.*
- The common suspension structure of each wheel splits into four independent suspension structures for the four wheels: *Fuse/Divide; Function Sharing*
- The core of the motorcycle (engine, seat, steering) remains the same while transforming into an ATV: *Common Core Structure* and *Shared Power Transmission.*

The transformer (motorcycle/ATV) is a preliminary concept embodying Transformation Principles and Transformation Facilitators. Current evolution of the device demonstrates the utility of the Transformation Design Theory and future work will be performed to fully embody the concept.

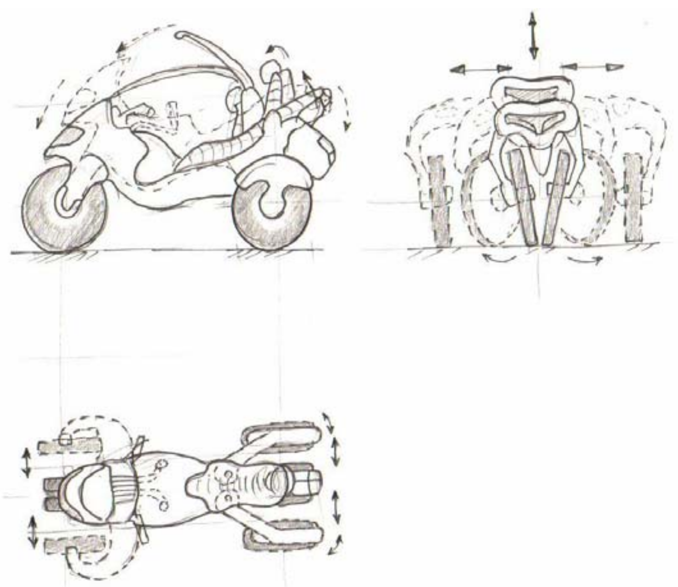


FIGURE 31. CONCEPT SKETCH OF A MOTORCYCLE-ATV TRANSFORMER

## 6.0 CONCLUSION AND FUTURE WORK

Devices that transform capture one’s imagination. They entertain and peek our curiosity, much like the childhood “Transformer” cartoons and toys. They perform multiple tasks and functionality beyond the single focus of most products. They expand the envelope of most creative and innovative thought. They seek to delight, efficiently and effectively, customers in ways that are unforeseen or forecast. But no foundation exists, beyond experiential approaches and serendipity, for understanding how to design and develop transformers. This paper utilizes a combined inductive and deductive research methodology for exploring transformation.

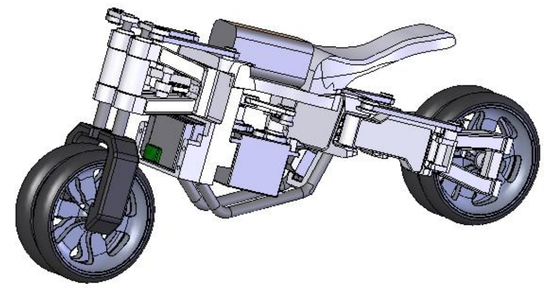


FIGURE 32. MOTORCYCLE CONFIGURATION

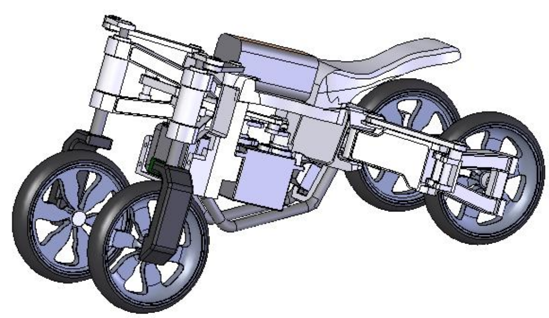


FIGURE 33. ATV CONFIGURATION

The results from this methodology are exciting. Three fundamental principles and a number of critical facilitators are presented and illustrated. These principles and facilitators form a budding theory of transformation in design. Initial results of implementing this theory, for example in unmanned aerial vehicle (UAV) technology [65], the motorcycle – ATV transformer and the generation of novel transformer concepts, are a clear indicator their potential in product development and beyond.

### 6.1 Future Work

Transformation Design Theory will be further studied by continuing and advancing the current research process. The research will progress into expanding the list of natural analogies, patents and products, refining the inductive and deductive principle extraction methodologies, further developing principles and identifying elements that are critical to transformation, and creating a design process for incorporating these principles into a generic design methodology for transformation. We seek to change the design culture's fundamental foundation by integrating Transformation Design Theory into different phases of a design process: identifying need for transformation during customer needs analyses, concept generation using principles and facilitators, inclusion of revolutionary technologies into transformational design, concept selection, product architecture transformational design analyses, optimization, design for robustness, prototyping etc.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge the support provided from the Cullen Endowed Professorship in Engineering, The University of Texas at Austin, and grants from the Air Force Research Laboratory Munitions Directorate (AFRL/MN) at Eglin, Florida and the Air Force Office of Scientific Research (AFOSR). The authors would also like to thank the Department of Engineering Mechanics at the U.S. Air Force Academy for their support and guidance. Any opinions, findings, or conclusions found in this paper are those of the authors and do not necessarily reflect the views of the sponsors.

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