How to design new grippers by analogy

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Abstract

Design by analogy is a powerful technique which, in spite of the ease of use, misses some structure to be exploited at maximum level. The paper investigates a possible system for structuring and expanding the possibilities related to the application of design-by-analogy. The proposed technique is applied to the design of novel grippers and some of these devices have been prototyped and tested. The study aims at: (i) increasing the design possibilities, (ii) analyzing and comparing standard industrial grippers and academic ones with different devices that share some functionalities with them and (iii) creating a repository that can be enlarged and reused for different applications.

Keywords

Design by analogy, functional analysis, gripper

Introduction and state of the art

Design by analogy is a useful methodology often adopted by professional designers, both at academic and industrial level. Sometimes the analogy technique is adopted considering only elements belonging to the same domain of the product under study (close-domain analogies). However, less often, different fields/sector are also investigated (cross domain analogies) to expand the design possibilities. [1][2]

The latter approach is extremely useful, especially during the starting phase of the conceptual design, because it allows to discover new ideas for the creation of novel products.

Nevertheless, while design by analogy is often performed without a formalized methodology in industry, different design theory and problem solving methods based on design by analogy do exist in literature. For example Synectics [3]
is a structured approach to the creative problem solving activity, based on analogical thinking. It identifies four different mechanisms which stimulates the creative thinking: direct analogy, personal analogy, symbolic and fantasy analogy.

A more structured method is the “theory of inventive problem solving” (TRIZ) [4]. The approach followed in TRIZ considers initially the abstraction of the problem, hence the identification of the contradictions, then the research of the solution by analogy within the 40 inventive principles. These principles have been extracted from a corpus of 2 million patents [4] and have been demonstrated to be stable with the passing of time [5].

Mc Adams et al. [6] provide a measure of the similarity of the products through the concept of functions and flows. Starting from the users’ needs, the functions that the product has to carry on are identified. After that, through an appropriate database, those products sharing a functional similarity are chosen for doing a cross over.

Also the method developed by Fantoni et al. [7] is focused on the concept of function. They described a technique based on functional analysis and on the analysis of functional synonyms and antonyms for the development of new ideas.

Another method which supports the design activity, stimulating at the same time creativity and the reasoning by analogy, is the wordTree design-by-analogy method [8]. This method systematically guides the designers in the identification of analogies and analogous domains thanks to the investigation of the lexical relationships among words (hyperonims, meronims, synonyms, etc.).

A huge source of inspiration for new solutions comes also from nature. Several works deal with the systematic transfer of biological knowledge into the engineering domain. Indeed, biomimetic design “offers enormous potential for inspiring new capabilities for exciting future technologies” [9]. Several researchers have used biological analogies for the generation of concepts ([10][11][12][13]).

In particular, through the concept of function, some of these works identify the biological elements to develop bio-inspired concepts. For example Shu et al. [14] combined functional modeling and biomimetic design, by incorporating biological phenomena into a function based design repository.

Similarly, Nagel et al. [15] presented a general method for the functional representation of biological systems through systematic design techniques.

The systematic search for inspiration in the biological field pushed the research towards the development of databases and softwares. For instance Chacrabarti [16] created a software called IDEA-INSPIRE, which uses a database of natural and artificial systems classified by a verb-noun-adjective triplet. Vincent and Mann [5] constructed a condensed TRIZ contradiction matrix (bio-triz matrix), that enables designer to abstract useful design information from biological systems.
Robotic research has always shown a deep interest in bio-inspired grasping principles [17]: one of the most interesting research activities is the gecko climbing system studied by Cutkosky's team. The climbing robot they developed is based on Van der Waals’ forces and hierarchical structures [18], while Matope et al. [19] transferred the concept to a microgripper.

The last element we want analyze is the abstraction. This stage plays a major role in the early stages of engineering design and is a valuable tool during the conceptual design phase[20]. Abstraction is also the first key step in TRIZ algorithm [4] while it plays also a relevant role in functional decomposition [21][22][23].

As seen before, different works resort to the concept of function, since it provides an abstract representation of the product. In engineering design, the definition or the comprehension of a system in terms of function, is a fundamental aspect ([24][25][26]) that helps the designer in conceptualizing and evolving the design. Functional Analysis (FA) helps the study of complex systems by breaking them down into simpler sub-functions.

Even more important, FA is fundamental in the conceptual stage of both original and adaptive design. Actually, during the 60s in Germany, a huge amount of mechanical engineering literature and practical efforts have been devoted to the development of catalogues of effects, principles and solutions. Those catalogues have the goal of providing abstract representations of the functioning of objects, in order to help the designer in choosing the best solution among all those able to solve the problem. Such a systematic encyclopaedia was developed by several authors and their results can be found in [27] and [21].

The early contributions on functional analysis belongs to Value Engineering [2728]. Later Collins [29] produced a list of all the mechanical functions that can be useful in a helicopter design. Pahl and Beitz [21] gave a fundamental contribution to the generalization of the field, introducing the notions of basic flows (material, energy, signal) and defined functions as operations on these flows.

Hundal [30] introduced a sixth general function (Branch) and, for each class, listed a series of functions in the form of "verb + object" on a specific flow. Then Szykman et al. [31] extracted a large body of terms after an extensive review of the literature, eliminating then synonyms and redundant descriptions. The effort promoted by NIST made soon evident the need for synthesis and reorganization. One of the attempts in this direction was promoted by Little et al. [32], who introduced the notion of functional basis. Stone and Wood [33] continued on the same track combining the classification of functions in classes with the structure of a basis. These efforts of synthesis culminated in the Reconciled Functional Base proposed by Hirtz et al. [34], where it is suggested a hierarchy of functions organized in three levels. Further flexibility is offered by the development of correspondents, or synonyms, whose number and name are left open.
Even if the RFB functional dictionary has been largely accepted and adopted, several works underlined the existence of various problems. Among them, Bonaccorsi et al. [35] developed a wide and interconnected functional dictionary, where vertical and horizontal relationships are mapped through synonyms and antonyms. Such extended dictionary offers the possibility of designing alternative solutions by using functional similarities or variants.

In the following paragraphs the paper presents our design by analogy approach based on functional analysis. An illustrative case of study is used to explore the application of the methodology to the design of new grippers. Then a number of issues and future directions are summarized in the final section of this paper.

The methodology

In order to overcome fixation and to explore also lateral ideas, we approached the problem of designing new products by using a crossover strategy (i.e. by using design by analogy). The idea behind is to find, in common days life, a source of novel ideas inspired by the objects used to carry on a desired function. A large database of these objects can be created in order to capture their behaviors, which concur to provide the researched functions. Each one of them can be described in functional terms (e.g. using the dictionary in [34] and [35]) to enhance their retrieval. Unfortunately, even if powerful, design by analogy is a very low structured technique, therefore, instead of starting with the analogies research, we propose two steps: first the generalization and abstraction of the problem, then the clusterisation of the results. While the first step enlarges the research domain, the second helps the designer in expanding the design space into each cluster.

How to apply the method

Even if the method can be easily understood, we would like to apply it to a real case in order to better illustrate the procedure through its steps. The application is the design of new grippers. Applying the design by analogy heuristic at the problem level without using a structured method, we can find interesting sources of ideas in new industrial grippers or in robotic hands, but such an analysis looks like much more a benchmarking than an inventive activity (Figure 1 left arrow). Actually, both the number and the diversity of the found analogies are reduced if compared to the more systematic analysis proposed here. For comparison the reader can refer to the seminal work of Novitskaya [36], where she attempts to demonstrate the similarity between grippers and some structures belonging to absolutely different technical systems. Even if the idea is correctly expressed and the case studied describes a gripping device, the approach is far from being systematic.
Figure 1. Sources of inspiration for design by analogy.

By abstracting (Figure 1 vertical arrow), and so generalizing the problem, the field of research can be enlarged. The abstracted problem can be described as follows: “to find a system able to reduce the degrees of freedom of an object”.

The research of solutions has been carried out through several brainstorming sessions and through several contributions developed independently by the participants. The goal was to identify the living beings and non living things that, through different mechanisms, perform the researched functions (Figure 1 right arrow and clusters).

Working by analogy the following areas have been explored:

- **biology and botany** (in a sort of biomimetic approach), varying from insects legs to animal trunks and tongues, investigating animal climbing systems or insects’ reproductive apparatuses or even plant glues or seeds shapes;

- **appliances and tools**, varying from snap-fits to locks, investigating gym devices as climbing cams or parachutes or even common day life tools as umbrellas and epilators;

- **weapons** as harpoons, varying from hook to hand harpoon, investigating simple or expanding bullet or even arrow or broadhead arrow;

- **clothes and accessories**, varying from belts to laces, investigating hairclip or nose-piercing or even zip or a button in a buttonhole.

*Functional decomposition of systems that grasp objects*
Whichever system is selected, standard gripper and robot hand, or novel “grasping” device, it has been analyzed in a formal way. For making the analysis as more rigorous as possible, a step-by-step top-down procedure has been chosen.

First of all, for each gripper, hand, device or animal, a suitable reference has been identified to clarify the functioning of the system of interest. This is important in particular to understand the correct behavior, especially for biological systems, which are not familiar for engineers. Then the decomposition moves towards the identification of the phases occurring during the utilization of the gripper, the actions performed by the animal or the use phases of the product. Actually, the identification of the phases makes it easier to create a detailed functional description. Then each phase is split into elementary functions and, to obtain homogeneous functional decompositions\(^1\), they are labeled by using the functional dictionary of Hirtz et al. \[34\]. At the end, each gripper is classified according to the physical effects involved during the functioning \[38\].

In particular, it is worth noting that the analysis of the elementary functions allows to map both the main function and also those functions supporting the grasping. In order to reduce ambiguities, the handling based on grasping has been split into standard phases and all the systems (included animals, devices etc..) are dealt according to such a set of phases (see Figure 2).

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\(^1\) The flows are not considered in the analysis since the aim is to develop a tool able to expand design by analogy between different domains and flows play a secondary role in such analysis. Flows variation and transformation have been described in \[7\].
in case of a mechanical two fingers gripper):

1. **approaching the object**: the gripper is open and the robot system positions it close to the object;

2. **coming into contact**: the gripper is actuated and its surface touches the object surface (in case of contactless handling the object is in the range of the force field generated by the gripper);

3. **increasing the grasping force**: the grasping force has to reach a value able to provide a stable grasping;

4. **securing the object**: the force stops increasing when the object stops moving independently from the gripper;

5. **lifting the object**: in such conditions the gripper and the object are joined and the object can be lifted (if the payload of both the robot and the gripper allows it);

6. **releasing the object**: at the macroscale, when the grasping force is removed, gravity helps to release the object. At the microscale the problem is more complex, therefore other releasing strategies has to be found [40];

7. **monitoring the grasp**: many different sensors (force and torque, stick-slip, contact sensors, etc.) are used to monitor the contact and the effectiveness of grasping.

Phases like number 1 and 5 are usually performed by a robot or other handling system, while phase number 7 can be done both locally, at the gripper level, or globally, at robot or environment level (through fixed cameras).

**Findings**

Nowadays grippers are changing toward a more and more complex design to accomplish the most various tasks. Even if research is pushing toward this direction, simple high efficiency grippers are still studied and produced for common industrial operations. Actually, high performances usually implies high costs, which are not possible in a competitive industrial scenario. Because of this fact high dexterous hands are mostly used in research activities or for particular manipulation cases, while simple and reliable grippers are intensively exploited in industry.
Figure 3 shows the space of automatic grasping devices. On the left side different industrial grippers are shown, while on the right one a few robot hands are presented. Examples of the two categories are vacuum cups, two finger mechanical jaw for the industrial grippers, and Vassura’s hand or Waseda University Hands [17] for what concerns the robotic end-effector.

The most important features for industrial grippers are the force, generally higher than in robotic devices, and the structural stiffness, which influences the quality of grasping, positioning etc. [17]. Moreover the reduced number of degrees of freedom increases the reliability of the gripper and reduces its cost. The robot hands, compared to the industrial grippers, have an higher compliance and dexterity (mainly due to the increased number of DOFs) that allow the manipulation of objects in a human-like way.

**Occurrence analysis**

*Standard grippers.* For each grasping principle [38] one standard gripper has been selected and analysed through functional analysis (Figure 4). Since the other grippers exploiting the same grasping principle show almost the same behaviour and the analysis can be considered nearly super imposable, a single device per principle is sufficient for the purpose. As a note, the functions related to the lifting and realising phases have been skipped, since they are repetitive and mainly based on robot capabilities and gravity, respectively.
Figure 4. Functional decomposition of the main grippers

Such decompositions can be considered as the baseline of the frequency analysis. The most occurring functions have been plotted in the Pareto’s histogram shown in Figure 5. As expected, the most repeated functional verbs are those related to the grasping and handling phases (to position, to bring close, to align, to connect, to mate, etc.). Some of them are peculiar to the grasping process, while others, such as to mate and to connect, show how grasping benefits from high coupling of gripper and object surfaces (often achieved through the deformability of the couple gripper/object).
“Non conventional” grasping systems. The methodology presented in the previous chapter has been applied to create a database that supports the designer, during the conceptual phase, in inventing new grippers. In order to overcome a rigid and convergent approach to the problem we decided to explore devices or living beings and non living systems that acts (also for short time periods) as grippers.

**Definition of gripper**

Grippers are defined as “a subsystems of handling mechanisms which provide temporary contact with the object to be grasped [...] and ensure the position and orientation when carrying and mating the object to the handling equipment[...]; the term “gripper” is also used in cases where no actual grasping, but rather holding of the object where the retention force can act on a point, line or surface [...]”[41].

So it is possible, and interesting, to find other systems not classified as grippers which match such a definition. Hence, a database made up of about 150 elements has been created (www.centropiaggio.unipi.it/~fantoni/D2_3_Grippers_by_analogy_final.xls). This database contains the names of the “non conventional” grippers and the relative functional decompositions of the grasping phases. The entries of the database are classified according to (i) the grasping mechanism (e.g. adhesion, grasping, pinching or punching) and (ii) to the fields whose they belong to (e.g. biology, appliances and tools, clothes and accessories, weapons, etc..).

Examples of convergent suggestions in the database are seat belts, fish nets, mechanical devices; more divergent ideas are for examples umbrellas, stents, car latches, etc. Moreover, even accidental and unwanted events as the nesting between springs or the tangling of trousers into a gear systems or in the bicycle chain can be useful for inspiring novel solutions for grasping.
Figure 6 shows a part of the database with elements satisfy the definition. For instance during the use of a parachute, it contains and constrains the air (it is a sort of temporary gripper for air). Another example is the brake that grasps/holds the wheel decreasing the vehicle velocity by friction. One more interesting object is the stent, that is inserted in the veins and arteries of the human body to counteract a localized flow constriction. Usually it is passed into the narrowed locations and then it is inflated. Thus the balloon pushes the metallic stent that crushes the fatty deposits, opening up the blood vessel and restoring the flow. Its functions of blocking the fat and holding the blood vessel in an open position satisfy the gripper definition.

Some entries of the database show the same functional decomposition therefore they can be considered identical, even if they are structurally different. These elements are in the column called correspondents. Indeed, the same functional chains can be carried out through different elements and even different physical principles. For example a plug, a stent and a latch perform the same functions to block and to hold.

Also for the non conventional grippers a frequency analysis has been performed, in order to identify where interesting changes emerge from the comparison of the two groups (conventional vs non conventional). Figure 7 shows the results concerning the top 30 functions.

<table>
<thead>
<tr>
<th>Analogy</th>
<th>Correspondent</th>
<th>Class</th>
<th>Coming into contact</th>
<th>Increasing the grasping force</th>
<th>...</th>
<th>Releasing</th>
</tr>
</thead>
<tbody>
<tr>
<td>pliers</td>
<td>birds, pleus,</td>
<td>A/B</td>
<td>position - bring close - contact</td>
<td>deform (pinch)</td>
<td>- deform (part)</td>
<td>- increase friction - block</td>
</tr>
<tr>
<td>clip for paper</td>
<td>A</td>
<td>contact - increase P - bring apart - move - increase friction - decrease P - bring close contact</td>
<td>deform - store o.o. - increase friction - block</td>
<td>move - increase friction - adapt (paper)</td>
<td>- allow DOF - separate - move (clip) - adapt</td>
<td></td>
</tr>
<tr>
<td>hair clamp</td>
<td>mouse trap, chodaxick, trap, peg</td>
<td>C</td>
<td>increase P - compress spring - store o.o. - bring apart - position - decrease P - bring close - contact</td>
<td>deform - store o.o. - increase friction - block</td>
<td>move - increase P - compress spring - store o.o. - bring apart - allow DOF - separate</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6. Screenshot of the database (full database at [www.centropiaggio.unipi.it/~fantoni/D2_3_Grippers_by_analogy_final.xls](http://www.centropiaggio.unipi.it/~fantoni/D2_3_Grippers_by_analogy_final.xls)).
In the case shown in Figure 7 the function "to deform" is split into two parts: gripper deformation and object deformation. The sum of gripper deformation and mating is relevant and their synergy plays a key role (even more important than in conventional grippers). This is probably due to the presence of biological systems, where the coupling of grasping device and objects surface is necessary to increase reliability and to decrease the amount of energy requested for the grasping (that, for example, is the base of the climbing of geckos, tree-frogs, squirrels, insects, etc.).

Case study

Robotic unloading of goods from containers

In time logistic companies are becoming more and more interested in automating the unloading of mass goods. The reasons rely on process cost and workers’ issues (long-term physical impacts, frequent absences due to chronic illness and high turnover). One of the most challenging problems is the grasping and handling of deformable and weight sacks (e.g. coffee and cocoa sacks) stacked and tangled one with the others. Such problem has to be solved in the RobLog project (Cognitive Robot for Automation of logistic Processes), whose purpose is to unload containers automatically. One of the basic steps of the project is the design of a grasping systems able to deal with objects having different properties, such as dimension, weight, porosity and flexibility. In the next paragraph some new grippers, which have been designed thanks to the presented methodology, will be shown.

Intrusive grippers.
At the present two workers use two hooks each to grasp and handle coffee sacks. The hooks pierce the jute sack, the two workers pull the sack from the pile, lift it and throw it over a pallet. The hooks (the steel wire has an average diameter of 4 mm) leaves small holes on the jute sack that can be tolerated within the process.

Intrusive grippers, as the above mentioned hooks, are frequently used in sacks handling or in food handling. The Schmaltz Gripper \([17][42]\) is a gripping system used for the handling of flexible, non-rigid components or materials which cannot be grasped by using vacuum, e.g. fabric sheets, textiles, foam materials. Its gripping behaviour is achieved by the intrusion of the needles within the fibers of the object. The same principle has been also adopted to handle frozen fillets of salmon or meat \([43]\).

Other techniques use of two rotating rollers able to entangle the textile of the sack \([44]\). The two rollers come into contact with each other and with the sack to be grasped. The rollers start counter-rotating while the sack textile is dragged by the friction forces and the sack moves into the end-effector. When a certain quantity of the sack is between the rollers, the sack can be lifted thanks to the forces exerted by the rollers. It really looks like to what happens when trousers come into the bicycle chain.

Kirchheim et al. \([45]\) described a gripper supplied with four “claw” systems with three concentric claws per system. The claw systems move vertically and rotate at 90° degrees. The edge of the claw pierces the jute, while the roto-translational motion produces the form closure. The gripper is really robust, but it requires a large amount of force to pierce the jute sack and to twist to assure the form closures.

This very short state of the art in coffee sacks handling showed that these four grippers (hooks, needles, rotating cylinders and claw) are similar to fish-hooks, forks, pull-over mill and a corkscrew, respectively. Such grippers are not automatized yet in an automatic unloading system and some of them suffer from reliability matter when the goods are irregular, nested, etc..

*Designed grippers*

The database (www.centropiaggio.unipi.it/~fantoni/D2_3_Grippers_by_analogy_final.xls) has been clustered and a limited number of concept has been extracted and implemented into real prototypes suitable for coffee sacks. Most of them can be used for the grasping and the lifting of heavy deformable objects, whose surface can be punched.

The following Figure 8 presents some of them.
Sewing Gripper. The concept of the gripper is based on that of sewing machine: a wire, in this case a metallic wire such as a spring, is sewn clockwise on the jute sack to be grasped by an electric motor. Once enough spires are inserted into the material, the grasping is performed and the sack can be pulled out. To release the objects, the spring is turned counterclockwise by the electric motor.

Inflatable gripper. The inflatable gripper changes its geometry to achieve the grasping. The main structure is a metal tube. A deformable membrane, surrounded by a braided sleeve, is the part of the gripper which deforms itself to switch from the insertion/extraction to the grasping configuration. The working principle is similar to the cited stent.

Cam gripper. This is an intrusive gripper, whose grasping capability is due to the contact between two or more metallic retractable shelves of the gripper, and the walls of the object to be grasped. The gripper is inserted into the object with
the shelves in the retracted position, then they are elongated and the object is pulled. To release the objects, the extensible components are retracted and the gripper is extracted.

*Reverse Scissor.* This gripper, like the ones presented above, is based on the intrusion principle. The rod with the two shelves aligned with its axis is inserted into the object. Then the shelves are rotated and blocked firmly in an opened position. Once the object is pulled to the final position, the shelves are rotated to the original configuration, then the whole gripper is extracted from the sack.

All the prototyped grippers (except the reverse scissors gripper that was made in ABS by rapid prototyping) demonstrated good grasping capabilities and a maximum pulling force varying from 200N to 350N. The holes generated into the jute sack remain within the specifications even if a miniaturisation process is necessary in the case of inflatable gripper and in general can be appreciated also in the other devices.

**Conclusions and future works**

In this paper a systematic methodology based on design by analogy has been presented. The method promote the search for analogies “out of the box”. The method, starting from the problem generalization, identifies the solutions (belonging to different fields from with common objects to living beings etc.) to the general problem and locates the found elements in a suitable database. The database contains for each element/object (that performs the macro-function of grasping in a particular way) also its detailed functional decompositions that allows further searches in the database.

The application of this framework allowed an extension of the solutions space both at theoretical level and at practical one. Actually, it has been also used as a guide to the design and prototyping of new grippers for coffee sack automatic handling.

The results we achieved are of interest for three reasons:

i) from a methodological point of view the process can be extended to other fields and the method can be used as a creativity support during the design phase;

ii) from the grasping side it is possible to notice that the grasping phase is highly affected by the ability of the gripper surface to couple with the object surface, the study of such adaptable surface can be the key to enhance (standard) gripper performances;

iii) design by analogy makes possible to conceive other grippers also in different fields as for example for grasping boxes, tires, pottery, etc.. The database
can be used a source for suggestions or extended in order to enlarge the design space for grasping and handling systems.

Funding acknowledgements

This work was supported by RobLog Project (FP7 ICT-270350) and LILIT Project (PAR FAS REGIONE TOSCANA Linea di Azione 1.1.a.3).

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