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A Strategy For Functional Design

Author: Y.C. Liu, Amaresh Chakrabarti, and Thomas Bligh

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1 Introduction

Generally, generating a large number of concepts is a good approach in the concept synthesis phase. Ullman [1] observed that designers tend to stick to their favourite ideas and refine them, which is restrictive. While the generation of a large number of ideas is advised, it is also true that this number must be reduced at the earliest possible opportunity because designers, in practice, are unable to consider many ideas in detail [2]. Although hundreds of product concepts may be found in the conceptual phase, only five to twenty will be seriously considered [3].

Many believe that an appropriate approach in conceptual design is to follow a style containing a divergent and a convergent step [4] [5] [6], in which at the divergent step a wide range of concepts[1] are generated, followed by an evaluation and selection of these at the convergent step. This approach prescribes that as many variations as possible should be generated in the divergent step, while the convergent step should consist of discarding ideas unlikely to lead to promising designs. This divergent-convergent approach increases the possibility of finding new ideas, and manages their number in a controllable way.

The problem of using this single divergent and convergent approach with a program such as FuncSION [7] which, for a given mechanical design problem, can produce an exhaustive set of solutions concepts in terms of their topological & spatial configurations, is that too many solution are generated to be seriously considered by designers. Moreover, the solutions generated by FuncSION are more abstract than the level of physical solutions, and therefore converting them into physical solutions will increase the number, and thus make this problem worse. This paper proposes a strategy for reducing the number of solutions at the earliest possible moment.

2 Method

In order to contain the number of ideas that can be meaningfully explored, we divide the divergent step into three levels, each of which contains a divergent and convergent step. In order to do this, the main questions are (1) What are the levels? (2) How would the steps in each level be carried out?

The three different levels of solutions proposed in this strategy are defined as (see Fig 1):

- **Topological Solutions**: are a form of combining a set of pre-defined primary elements in series. Each element is represented as a certain function with an input at one end and an output at the other. For instance, a *crank* element is used to transfer from a force at the

[1]The terms, 'concept' and 'physical solution' are used interchangeably in this paper, and they are similar to 'solution principle' in design research literature [2] [4] [6].

input to a torque at the output. The interconnection between primary elements is either force or torque.

- **Spatial Solutions**: are described as a combination of a set of spatial pin elements. Each element is used for the abstract representation of how the possible embodiment of each function is oriented in space. Take the *crank* element as an example; it has various possible orientations in space in terms of pin like representations, with the condition that the spatial orientations of the input and output of each pin element have a definite relationship: orthogonal and non-intersecting to each other. Connections between these elements contain types and directions of force or torque, and positions for each possible embodiment.

- **Physical Solutions**: are composed of a set of components and their interfaces at the geometric level. Components are presented qualitatively. Dimension is not considered in this solution level. The connection between components is the interface which determines the relative kinematic behaviours of the adjoining components.

  The main difference between these three levels is that topological solutions are generated in terms of a set of labelled functions under the consideration of how the type of energy flow can be transferred from the input point to the output point; spatial solutions are represented in terms of three dimensional configurations based on how the types and directions of energy flow of input and output are transferred, as well as on how possible components of each element are oriented and positioned; physical solutions contain geometric forms and interfaces.

The three convergent-divergent stages, from functional requirements to physical solutions, are described as follows:

1. **From functional requirements to topological solutions**

   Divergence (kind synthesis): This involves generating variations in terms of number and types of primary elements. Having arbitrarily chosen the maximum allowable number of elements to be used in a design solution, the procedure generates each distinct labelled directed path. The designer input for divergence is to choose a set of primary elements form the database and specify the input and output in terms of force or torque.

   Convergence (heuristic screening): Based on an understanding of possible geometric embodiments of the topological solutions, and their kinematic behaviour, rules for proving their solutions based on similarity are developed. For instance, a solution having a shaft connected to a shaft is equivalent to one having a single shaft. The solutions can also be proven using the desired temporal behaviour and the required magnitude ratio (to be specified by the designer) between input and output [8]. These lead to a set of rules for achieving convergence.

2. **From topological solutions to spatial solutions**

   Divergence (spatial synthesis): This involves generating spatial variations for the topological solutions from the last step. Each element is divided into various pin like orientations. Considering all possible orientations of each element in a solution, its alternative spatial configurations, which meet the rules of connection, are generated. The designer input for spatial synthesis is to specify the input and output in terms of the direction of force or torque.

   Convergence (position screening): This involves discarding those solutions which fail to meet the relative position of the input and the output point. Some solutions, which do not work at the next instant of time or do not have possible embodiments, could be discarded here. The designer input here is to specify the relative position of the input point and the output point.

3. **From spatial solutions to physical solutions**

   Divergence (physical synthesis): Here variations in terms of geometric components and interfaces are generated for each spatial solution. This contains the steps of considering all possible physical components for each spatial element in a solution, generating all possible combinations of these components, and ensuring appropriate interfaces between connecting components are available.

   Convergence (functionality screening): At this level, solutions failing to meet functional requirements are discarded. Some key requirements like the magnitude ratio, and the kinematic performance are considered here. The designer input here, is to specify the kinematic performance, such as linear or nonlinear, or continuous or intermittent.

3 Results

The example presented here is to demonstrate how physical solutions are generated in our design process, which first generates topological solutions, then converts these into spatial solutions, and finally translates these solutions into physical solutions. The representation at each solution level is shown in Fig 1. Let a door latch design require a torque input, T, in the direction of j+, applied on the door, and the latch output to be a force, F, in the direction of i-, to enable disengagement of the latch from the door frame, for a maximum allowable number of elements of 3. The topological solutions after kind synthesis are shown in Fig 1(b). One of the topological solutions is selected, seen in the rectangle. Fig 1(c) shows some of its spatial configurations. Fig 1(d) presents some of the physical solutions from a specified spatial solution (encircled).

Fig 2 describes the number of solutions generated by FuncSION with one divergent step (dashed lines), and the proposed alternative multi-divergent-convergent steps (solid lines) in the given design problem, in which the maximum allowable number of elements is 2. The number of topological solutions with and without the convergent step is 6 and 15 respectively, the number of spatial solutions with and without the convergent step is 9 and 23, and the number of physical solutions with and without the convergent step is 49 and 112. The result of this approach shows a substantial reduction in the number of solutions generated by FuncSION.

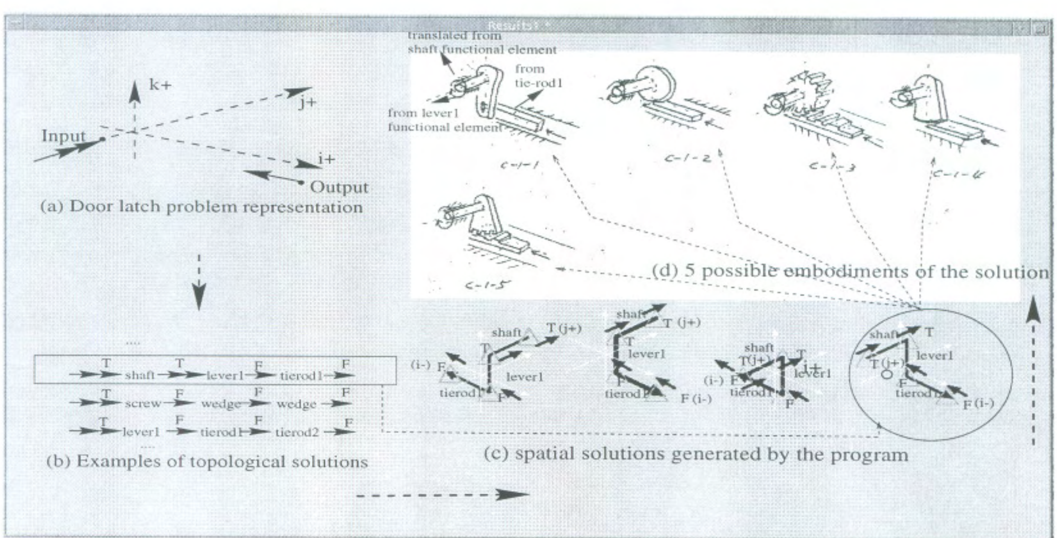

Figure 1: Solutions represented at various levels

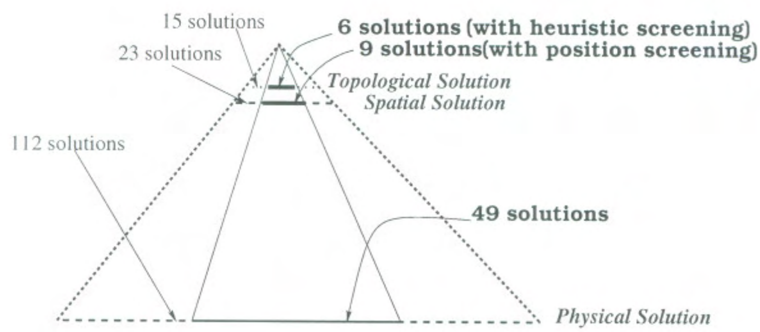

Figure 2: The number of solutions at three different levels

4 Conclusion

This paper discusses a new strategy for functional design, in which a process of multiple divergence and convergence is used. Expansion of solutions consists three synthesis processes, namely: kind synthesis, spatial synthesis, and physical synthesis. The processes of narrowing down solutions are screenings based on: seemingly simple but powerful heuristic rules for discarding similar and infeasible solutions, the relative position of input and output, and functionality. Comparison of this approach with the previous results shows that the number of solutions to be considered by designers is now reduced substantially.

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First authors name: Ying-Chieh Liu
Institution/University: University of Cambridge
Department: Department of Engineering
Address: Department of Engineering, Trumpington Street, Cambridge CB2 1PZ
Country: UK
Phone: +44-1223-332828
Fax: +44-1223-332662
E-mail: ycl27@eng.cam.ac.uk