A Comprehensive Behavioural Process Model for Design Synthesis

Yi-Min Deng [1, a], Yongsheng Ma [2,b], Meiyan Wang [3,c], Liang Shi [1, d]

[1] Department of Mechanical Engineering, Faculty of Mechanical Engineering and Mechanics, Ningbo University, Ningbo City, Zhejiang Province 315211, P.R. China

[2] Department of Mechanical Engineering, Faculty of Engineering, 4-9, Mechanical Engineering Building, University of Alberta, Edmonton, Alberta T6G 2G8, Canada

[3] Department of Precision Machinery and Precision Instrumentation, University of Science and Technology of China, Hefei city, Anhui Province 230027, P. R. China

[a] dengyimin@nbu.edu.cn, [b] yongsheng.ma@ualberta.ca, [c] yiqun@mail.ustc.edu.cn, [d] sliang212@163.com

Keywords: Behavioural process; Design synthesis; Relation and characterization.

Abstract. Design synthesis is a critical activity for the development of design solutions. Although there are already quite some design synthesis models for the conceptual phase of product design, there still lacks a comprehensive model that takes into account extensive aspects of behavioural process characteristics, which are essential for the development of design solutions. In this paper, the characteristics of behavioural process are investigated and a number of inherent relations and characterization within a behavioural process are identified, including temporal relation, loop relation and state characterization, in addition to the existing causal relation. A comprehensive behavioural process model is subsequently developed, where the identified relations and characterization, together with the behavioural process development procedure are incorporated. The model can be used in explicitly exploring the behavioural process characteristics and thus assisting the designers in synthesis for design solutions. A design case study is also presented to illustrate as well as to verify the proposed methodologies.

Introduction

Design synthesis includes the identification of one or more design solutions consistent with the design requirements and any additional requirements identified during synthesis [1]. To assist design synthesis, it is generally necessary to exploit the relevant behaviour information. This is because behaviour is a bridge to link the gap between function and physical structure [2]. For example, in the Function-Behaviour-Structure design model proposed by Qian and Gero [3], behaviour is categorized as the expected behaviour that is desired by the design in fulfilling a required function, and the actual behaviour that is performed by the product structure. Expected behaviour is derived from a formulation or specification of the design problem. Actual behaviour is derived from analysis of a database of existing structures. In this way, a synthesis method is proposed to generate the actual behaviour from the expected behaviour. Other behaviour related synthesis models include the Function-Behaviour-State design model [4, 5], the causal behavioural process design model [6-8], and so on.

It is noted that all these synthesis models have exploited one or two aspects of behavioural characteristics but none has incorporated all. Besides, there could be more than those identified aspects of characteristics, which are also useful for design synthesis. For example, in the Function-Behaviour-State model [4, 5], behaviour is regarded as a physical state transition of the behaviour actor. In the Causal Behavioural Process model [6-8], it is regarded as the physical interactions between the behaviour actor and its environment, including the input actions to the behaviour actor and the output actions from it; hence the synthesis model exploits only the causality information of behaviours.

To address this problem, this paper shall make an investigation of all aspects of behavioural characteristics and propose a comprehensive behavioural process model to assist the development of conceptual design solutions.

Behavioural Process Characteristics

By studying a number of mechanical and electromechanical devices, we noticed that there exist some inherent relations and characterization within behavioural processes.

Causal relation. A behavioural process consists of a number of individual behaviours. Each behaviour exhibits a number of input actions and output actions. Between two adjacent behaviours, an output action from the proceeding behaviour actually works as one of the input actions to the succeeding behaviour, hence the proceeding behaviour can be regarded as the "cause" for the occurrence of its succeeding behaviour. Together, the individual behaviours form a network, which is referred to as a Causal Behavioural Process (CBP) [6-8]. Among all the input actions and output actions, some input actions may come from the environment, while some output actions may be delivered to the environment. These are the input and output actions of the entire behavioural process. The causal relations between adjacent behaviours of a behavioural process characterize the causality of the behavioural process. This is one of the most essential characteristics of a behavioural process, given its critical role in establishing the dependency between individual behaviours thus the formulation of the behavioural process.

Temporal relation. Each individual behaviour of a behavioural process shall occur for a certain amount of time; it could be long or just a short instance. Multiple behaviours may occur simultaneously or one after another. Hence, there exists temporal relation among individual behaviours, which indicates the concurrency or sequential characteristics of the behaviours. This information is useful for design synthesis. For example, when two or more individual behaviours need to utilize a same energy or material resource, the temporal relation information may help the designers in determining how the individual behaviours should use the resource, including the sequence, the duration, as well as the concurrency, and so forth. Temporal relation may be utilized not only in design synthesis, but also in design evaluation and verification [9].

Loop relation. For some utility devices such as the automatic mounting devices, automatic press fitting devices, electric or pneumatic nailing devices, etc., there is generally such a phenomenon within the behavioural process of the devices in that, all the movable components of the devices will return to the initial state after finishing their corresponding behavioural process. This is to ensure that the device can be ready for another round of behavioural process. In doing this, the behavioural process shall have a trigger behaviour and a revert behaviour, where the former is used to trigger the start of a single behavioural process, while the latter is used to revert the moving components of the device to its initial physical status, including position, orientation, velocity, etc. As such, the relevant behaviours have for a loop relation. In fact, there could be multiple loops within such a behavioural process, hence they are also referred to as *phenyl loops*. There are also some rules and characteristics regulating the phenyl loop relations [10].

State characterization. The above relations all characterize mutual relations between individual behaviours of a behavioural process. However, an individual behaviour itself shall also exhibit some useful characteristics which are useful for design synthesis. In fact, the behaviour actor may exhibit multiple physical states during the occurrence of the behaviour. The state transition may be triggered by different working conditions; or they may be triggered by the other individual behaviours of the behavioural process. The state characterization of behaviours shall be discussed further later.

Behavioural Process Model for Design Synthesis

With the above relations and characterization of behavioural process, we propose a comprehensive behavioural process model for design synthesis, as is illustrated in Fig.1. This model consists of three layers of design information, namely, function layer, behaviour layer and structure layer. In the function layer, design synthesis is materialized as a function decomposition, from which a function structure proposed by Pahl and Beitz [11] would be generated. For example, Fig. 1 shows that the overall function F0 is decomposed into three sub-functions, F1 – F3. The sub-functions are then mapped to structure either directly, such as F3 is mapped to S3; or via a single behaviour, such as F2 is mapped to S2 via behaviour B8; or it may need to develop a behavioural process first before an implementing physical structure can be identified, such as the behaviour process (behaviours B1-B7) for mapping F1 to S1.

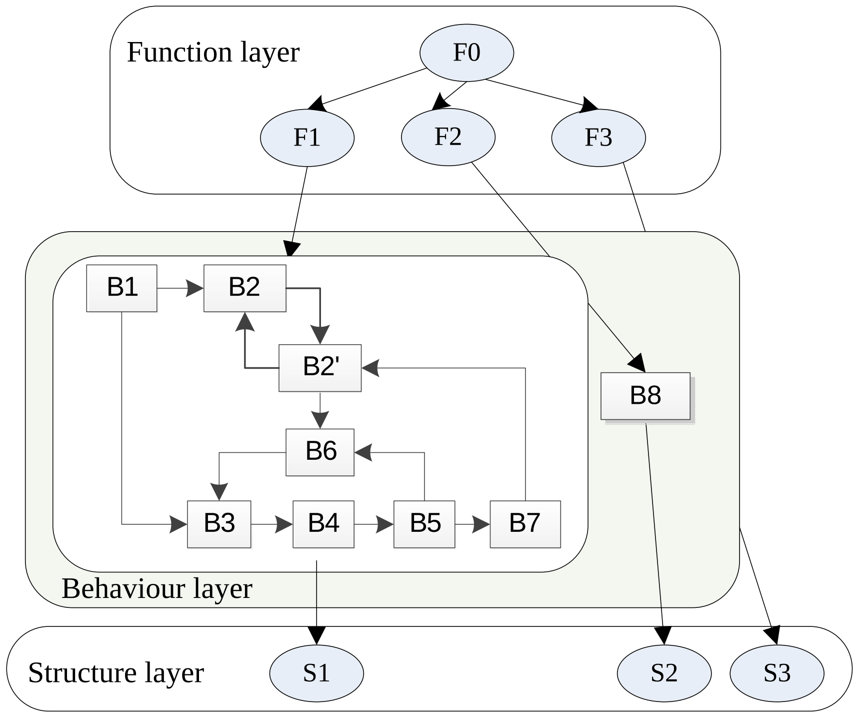

Fig.1 Illustration of the proposed design synthesis model

In the design synthesis process, a direct mapping is always carried out first for all the decomposed sub-functions. If this fails, then mapping via a single behaviour is tried. Either direct mapping or mapping via a single behaviour may be assisted by past design knowledge stored *a priori*. This is often referred to as the *design catalogue approach*. If, however, it is found that it is not feasible for a single behaviour to fulfil a required function, then the development of a behavioural process will be necessary. During this process, the aforementioned causal, temporal and loop relations, as well as the state characterization can be applied to assist the development of a feasible behavioural process, where the behaviour actors of all the constituent individual behaviours can subsequently be constructed to offer a physical solution to the corresponding function.

For example, in developing the behavioural process shown in Fig.1, a backward reasoning process proposed by Deng et al. [6-8] may be applied to identify individual behaviours B7, B5, B4 and B3, where the causal relations between the adjacent individual behaviours are utilized. In developing B6, the loop relation is exploited to ensure that the corresponding part of the device can revert to its initial physical status each time the behavioural process is fulfilled. From B7 to B1, there are two individual behaviours B2 and B2’, both of which are actually exhibited by a same physical structure, but are associated with different physical states. Hence, they are also referred to as *state behaviours*. With the driving input from B1, B2 changes the physical state from one to another. B7 is the trigger behaviour of this behavioural process. B2’ resets the structure state and generates a functional output to B6.

Case Study

In this section, we shall study a simple electric nailing device to illustrate how the proposed behavioural process model can be applied for design synthesis. The overall function of the device is to strike nails into an object quickly and repeatedly, indicated as F0. By applying the proposed model, functional decomposition should be carried out first to develop a function structure of the design problem. After that, each sub-function shall be mapped to structure either directly or via a single behaviour or a behavioural process. To simplify our discussion, we shall study the development of a behavioural process, as is shown in Fig.2, for one of the sub-functions "to strike the nail with a working head and revert the working head", indicated as F1. By exploiting past design experience, an individual behaviour B1 is developed, which is to generate a magnetic force with a magnetic field. The driving input to B1 is that of the electric power supply, which is readily available as has been specified in the given design problem. With the output actions from B1, i.e. the striking force, B2 is developed, which is to strike the nail with a working head. Hence, part of the functional requirement of F1 has been fulfilled.

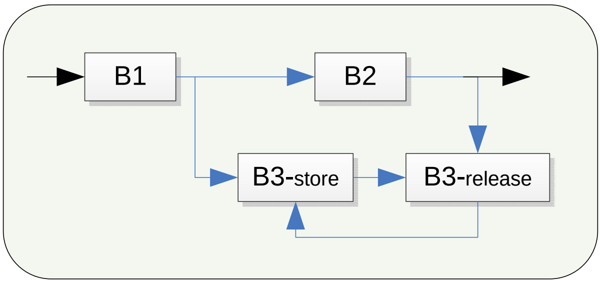

Fig.2 Behavioural process development of a design case

To fulfil the remaining functional requirement specified in F1, we need to provide a yet another force to push the working head back after each striking action. In doing this, the state behaviours proposed in the previous section may be employed. We may, for example, utilize energy storage mechanism [12] by using a compression spring to deliver the two state behaviours, i.e. B3-store and B3-release, as are shown in Fig. 2. B3-store is the behaviour of the spring in storing energy (the spring is being compressed) when the working head is moving forward; whereas B3-release is the behaviour of releasing energy when the working head is moving back. This solution effectively addressed the design requirement in that, there is no additional outside energy required to provide the revert action; besides, the mechanism is relatively simple.

Further more, it is necessary to exploit the temporal relations within the developed behavioural process to verify whether the developed structural solution can work appropriately. Still further, when combining all of the developed behavioural processes (which are for the decomposed sub-functions respectively) to form the overall behavioural process of the design, it is necessary to apply the loop relation to ensure that the whole device can revert to its initial status after each striking action (not just the working head – the next nail should also be in position for the next striking action). Due to the space constraint, these are not further discussed.

Conclusions

In the previous sections, we have studied the characteristics of the behavioural process and proposed some additional inherent relations and characterizations within a behavioural process other than the existing causal relation, including temporal relation, loop relation and state characterization. These characteristics are then utilized to develop a comprehensive design synthesis model, where the development of behavioural process to assist function to structure mapping is elaborated. A simple case study demonstrates that the model is useful in assisting designers to develop effective design solutions. Further work is needed in applying the model to more design case studies and if necessary, to modify and refine it, so that it can be applied to more complex design problems.

Acknowledgements: This work was supported by the National Natural Science Foundation of China (Grant No. 50875133). It was also supported by a project titled Design Methodology Research for Assembly Systems from the Foreign Experts Affairs Bureau of Ningbo, China.

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