5 HOW ENGINEERS SYNTHESIZE MULTIPLE STATE MECHANICAL DEVICES: AN OBSERVATIONAL STUDY

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Automated synthesis of mechanical designs is an important step towards the development of an intelligent CAD system. Research into methods for supporting conceptual design using automated synthesis has attracted much attention in the past decades. The research work presented here is on ten design synthesis processes of multiple state mechanical devices done by engineering designers. The ten design synthesis processes are video recorded. The video records are transcribed and coded for activities occurring in the synthesis processes, input to and output of the activities. This will be used to identify the outstanding issues to be used as a basis for developing a support system for automating the design synthesis of multiple state mechanical devices.

Keywords: Automated-synthesis, Multiple-state, Design, Mechanical-device.

1. INTRODUCTION

Research into methods for automating the conceptual phase of the design process has attracted much attention in the past decades. A major difficulty in conceptual design task is that not many potential solutions are considered by the designer during the design process.[1–3] The major causes for this difficulty are possible bias towards a limited set of ideas during the design process, time constraint and the tendency to delimit a design problem area too narrowly and thus not being able to diversify the possible set of design solutions.[2,4] Therefore, a support system, automated or interactive, that can help generate feasible design alternatives at the conceptual design phase is important to the development of intelligent CAD tools that can play a more active role in the mechanical design process.

Li[4] defined the operating state of a mechanical device by a set of relations between its input and output motions. This set of relations remains unchanged within an operating state. A multiple state device has a different set of relations between input and output motions in each operating state. Adapting the definition of Li[4], we define the state of a mechanical device as follows. Let there be a device with a set L= $\{L_1, L_2, L_3 \ldots. L_m\}$ of input or output components in different states. The components on which we apply an effort are taken as input components. The components for which we desire the final outcome of the effort are taken as output components. The set of components, L of the device has a set of configurations, C= $\{C_1, C_2, C_3 \ldots C_n\}$, where Ck = $\{a_1, a_2, a_3, \ldots, a_m\}$ and ai is the configuration (position or orientation) of L_i. The behavior of the device can be represented as a set of states and state transitions, where a state(S_p) can be a change in configuration, C_{pq} (C_p to C_q) of L, due to an effort on any component of L, or no change in configuration Cpp of L, due to a non-zero effort on some components of L. A state transition Spq is defined as a change of state from C_{pr} to C_{rq}. Other researchers[5–8] defined operating state (hence forth referred to as state) in various other ways.

2. RESEARCH PLAN

The central research question to be addressed is — how to synthesize, automatically or interactively, a comprehensive set of possible device concepts that satisfy multiple states? The sub questions are: how to represent multiple state design tasks and devices?, how to analyze the functioning of multiple state mechanical devices? and how to automatically or interactively synthesize a comprehensive set of multiple state devices?. The questions are to be addressed through the following: literature study, study of synthesis done by the researcher, study of synthesis done by other designers, development of support for progressive automation of the synthesis process for multiple state design tasks, and evaluation of the support.

The objective of this paper is to understand how synthesis of multiple state devices is carried out by designers. A multi-state design task is specified using states and their transitions. Ten designers, including the researcher, are given this design problem and asked to generate as many design alternatives as possible. The processes are video recorded using a 'think-aloud' protocol, which are analyzed to identify the generic structure of the processes and their outcomes. This understanding should help develop the support.

3. LITERATURE STUDY

Research on synthesis of multiple state mechanical devices has been carried out primarily by Li.[4] He has used configuration space approach to represent and retrieve the behavior of a kinematic pair and developed ADCS (Automatic Design by Configuration Space) for the automated synthesis of multiple state mechanical devices. The present implementation of ADCS is limited to kinematic pairs with fixed motion axes, kinematic pairs with two dimensional configuration spaces, design problems with only two motion axes, and, is able to generate only one solution at a time.

Most of the other existing work[9–18] is limited to single state design problems. The major problem with the single state approach is in the representation of the building blocks. The relation between the input and output of a building block is characterized by a single set of relations. These relations are considered fixed during the operation of the device. This limits the single state approach to solve multiple state design problems where the relations between input and output change between different operating states.

4. SELF STUDY

Here a door latch problem is used as the case for analysis and synthesis. This section shows the results of the analyzing the video protocols of the researcher himself.

4.1. Analysis of Multiple State Mechanical Device

An existing door latch is modeled as in Figure 1. The latch has an L-shaped handle hinged at A, a torsional spring connected to the handle at A, a block, a rod attached to the block and a spring arrangement, where the spring is confined between the block and support with a hole through which the rod can translate, a small pin attached to the rod protruding perpendicular to the plane of the paper, and a stop at C.

The door latch has five states as shown in Figure 2 and Figure 3. In Figure 2, states are explained through the model of door latch and in Figure 2, states and state transitions are explained through initial and final configurations of input and output elements. Multi-state design problem of the door latch is as follows. It has two components, handle L_1 and block L_2, acting as input or output components in different states. L1 and L2 has configuration parameters Θ and X respectively. So L= set of input and output components= L_1, L_2, C= set of configurations= $\{C_1, C_2, C_3\}$, where $C_1 = (0, 0)$, $C_2 = (\Theta_a, x_1)$ and $C_3 = (0, x_2)$. Now the behavior of the latch be represented as a set of states and state transitions, where State 1 is a change in configuration from C_1 to C_2 of L, due to a torque on L_1, State 2 is no change in configuration C_2 of L, due to a non-zero torque on L_1, State 3 is a change in configuration C_2 to C_1 of L, due to release of torque on L_1, State 4 is a change in configuration C_1 to

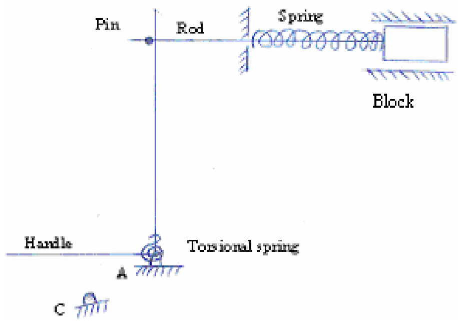


Figure 1. Model of a door latch.

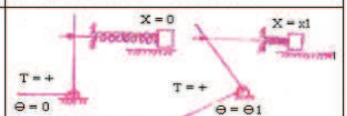
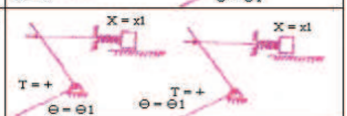
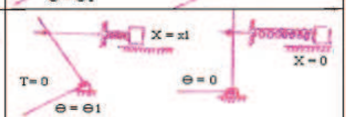
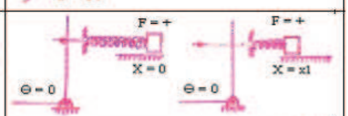
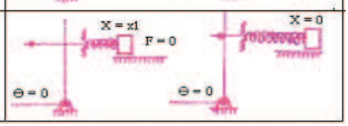
State description	Initial and final configurations in that state
In state1, at C1 = (0, 0), the configuration changes from C1 to C2 = (Θ1, x1) due to application of torque(in counter clockwise direction) on the handle.	
In state2, at C2 = (Θ1, x1),there is no configuration change in C2, though torque (in CCW direction) is applied on the handle.	
In state3, the configuration changes from C2 = (Θ1, x1) to C1 = (0, 0) due to release of torque on the handle.	
In state4, the configuration changes from C1 = (0, 0) to C3 = (0, x2) due to application of force on the block.	
In state5, the configuration changes from C3 = (0, x2) to C1 = (0, 0) due to release of force on the block.	

Figure 2. Multi-state diagrammatic representation for door latch.

C_3 of L, due to a force on L_2 and State 5 is a change in configuration, C_3 to C_1 of L due to release of force on L_2.

4.2. Synthesis of Multiple State Mechanical Devices

After analyzing the given problem, State 1 was selected and rack and pinion, slider crank mechanism, rope and drum and cam and follower were generated as shown in Figure 4(a)–(d); four handles were generated as shown in Figure 4(e)–(h). These handles were evaluated and it was found that two, shown in Figure 4(g) and Figure 4(h) were better suited; the other two were rejected. The four mechanisms, shown in Figure 4(a)–(d), were evaluated for State 1. Cam and follower, as shown in Figure 4(d)) failed to satisfy axis transition requirements of State 1. It was modified into two alternatives, shown in Figure 4(i)–(j). With three possible joints (Figure 4(k)–(m)) between the two selected handles, Figure 4(g)–(h), and five mechanisms (Figure 4(a)–(c) and Figure 4(i)–(j)), 30 alternatives were created to satisfy State 1. Next three arrangements (Figure 4(n)–(p)) were generated to satisfy both State 1 and State 2. So $30\times3=$ 90 alternatives for satisfying State 1 and State 2 were generated. Next a torsional spring was generated for State 3, and the alternatives were modified by adding the spring.

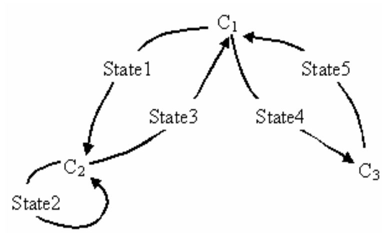


Figure 3. Initial and final configurations of each state for multi-state door latch design task.

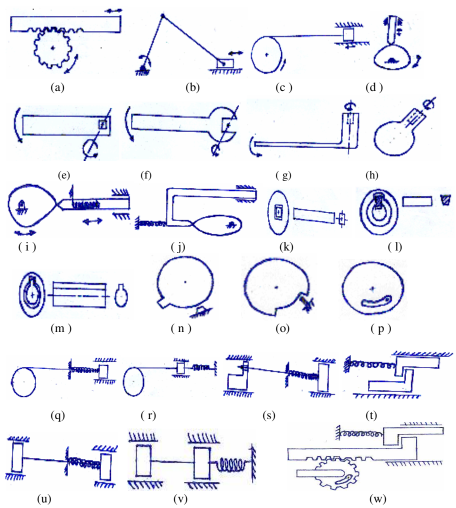


Figure 4. Synthesis done by the researcher.

All were evaluated for State 1-State 3. The eighteen alternatives that use rope and drum (Figure 4(c)) did not satisfy State 3. These were modified by removing torsional spring and adding a tensile or compression spring, producing 36 alternatives using drum and rope. Two of these 36 are shown in Figure 4(q)–(r). All these 108 alternatives were evaluated for State 4. All except the 36 alternatives that use rope and drum and 18 alternatives that use cam and follower (Figure 4(j)) failed to satisfy State 4. A new multi-state design problem using State 1-State 4 was formulated. Four alternatives were generated (Figure 4(s)–(u)) for this new multi-state design task and these four were integrated into the 54 mechanisms, which satisfied State 1-State 3 but not State 4. So 270 (=18+ 36+ (54*4)) alternatives satisfied State 1- State 4. All these 270 were evaluated for State 5 and satisfy State 5. So 270 solutions were synthesized, which satisfied all the five states. One of those formed from Figure 4(a), (g), (k),(p) and (t) is shown in Figure 4(w).

5. STUDY OF SYNTHESIS DONE BY NINE OTHER DESIGNERS

Each designer was given the above multiple state door latch design task and asked to develop individually, without time constraint, as many solutions as possible.

Designer1 selected State 1, generated the solution proposal shown in Figure 5(a) for State 1, modified it by adding a grounded obstruction for State 2 and a linear spring for State 3, evaluated it against State 4 and State 5 and found that all states were satisfied and arrived at the solution shown in Figure 5(b).

Designer2 selected State 1, generated the proposal shown in Figure 5(c) and modified it by adding a grounded obstruction for State 2, and springs for State 3. He evaluated it against State 4 and State 5. As they were satisfied and solution was generated as in Figure 5(d).

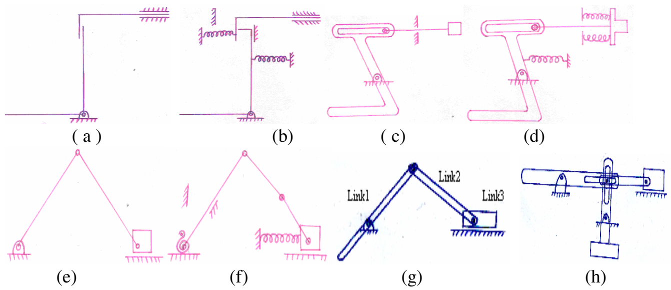


Figure 5. Synthesis done by Designer1, Designer2, Designer3 and Designer4.

Designer3 selected a two step strategy. In Step1, he generated a proposal to convert rotary motion of Component 1 to translatory motion of Component 2 and translatory motion of Component 2 to rotary motion of Component 1. In Step2, he modified the proposal such that rotary motion of Component 1 gives translatory motion of Component 2 and translatory motion of Component 2 does not give rotary motion of Component 1. He generated a slider crank mechanism for Step1 (Figure 5(e)) and modified it by adding grounded obstruction near the crank for State 2. He modified again by adding a torsional spring and linear spring for State 3 and replaced the connecting rod with two links connected by a hinge for Step2. His finally synthesized solution shown in Figure 5(f).

Designer4 generated a slider crank mechanism (Figure 5(g)) for State 1 and modified it by adding Link4 for State 2. He modified the crank (Link1) with a slot for State 1 and State 2, a slot in and a mass to Link4 for State 3. For State 4, he modified the alignment of Link1 and 2. This also satisfied State 5 and solution was arrived as in Figure 5(h).

For State 1, Designer5 generated a slider-crank mechanism as in Figure 6(a). He modified it by adding a grounded obstruction for State 2, a linear spring to the slider for state3 and a slot in the slider for State 4. As State 5 was also satisfied, a final solution was synthesized as shown in Figure 6(b).

Designer6 generated two alternatives, Figure 5(c)–(d), for Component 1 motions and the two alternatives, Figure 6(e)–(f) for Component 2 motions, from all the states. For State 1, he joined these with a rope to produce four alternatives. For State 2, he modified the disk shape and added a grounded obstruction. Two of the alternatives are shown in Figure 6(g)–(h).

Designer7 generated a strategy to develop a solution using gears. After generating a gear pair, he modified it with a follower and added a connecting rod for State 1 as shown in Figure 6(i). He modified the gear shape with a slot and a pin in the slot for State 2 and added a torsional spring for State 3. For State 4, the follower was kept in a cylindrical shaped component. As this modification failed State 3, he modified it by adding a linear spring. As State 4 and State 5 were also satisfied, final solution was arrived at as shown in Figure 6(j).

Designer8 selected State 1 and generated two proposals as shown in Figure 6(m)–(n). He modified these by adding a grounded obstruction for State 2 and springs for State 3, and evaluated these for State 4- State 5. As they were satisfied, he arrived at two solutions as shown in Figure6 (k)–(l)

Designer9 selected the strategy of generating a solution proposal for State 4 and State 5 and modifying it for State 1- State 3. He generated a solution proposal as shown in Figure 6(o). For State 1, he modified the proposal by adding projections on it and adding a circular disk, which also had a projection on it. For State 3, a torsional spring was added to the circular disk. State 4 and State 5 were evaluated and found to be satisfied. His solution is shown in Figure 5(p). For State 4 and State 5, he again started with the proposal in Figure 6(o) and modified it for State 1-State 3 as shown in Figure 6(p). He again selected a strategy to develop a solution using the concept of cam profile. For State 4 and 5, he used the proposal in Figure 6(o) and modified it for State 1-State 3, as shown in Figure 6(r). He selected a strategy to develop a solution using a flexible element like string. He synthesized two solutions as shown in Figure 6(s)–(t).

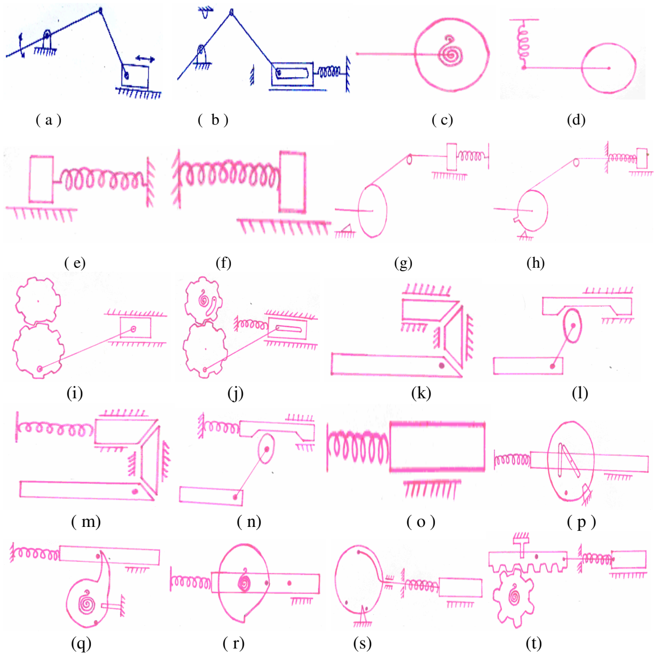


Figure 6. Synthesis done by Designer5, Designer6, Designer7, Designer8 and Designer9.

6. OBSERVATIONS FROM THE ABOVE SYNTHESIS PROCESSES

All the ten video records of synthesis processes are transcribed and coded for activities, which are analyzed to understand the process of synthesis in greater detail, and provide a basis for supporting the synthesis process at the various levels of automation. *Analyze, Select, Generate, Evaluate* and *Modify* are the five primary level activities observed to occur in the synthesis processes. *Analyze* is to consider something in detail in order to discover essential features. *Select* is to pick out something from a number of alternatives. *Generate* is to produce something. Generate has two secondary level activities of *Retrieve* and *Derive. Retrieve* is to bring back something and *Rerive* is to deduce from something. Evaluate is to validate something with respect to something. *Modify* is to change something. *Modify* had secondary activities like *Add, Replace*, and *Incorporate. Add* is to combine with existing things. Replace is to substitute a thing for another. *Incorporate* is to merge something with something already in existence. An example of coding activity is shown in Table 1. The nomenclature is as follows: SP111 is solution proposal111 (SP1 is the initial solution proposal. Each time it is modified, 1 is added to it), ST1 is State 1, P is the given multistate design problem, ST1/P is State 1 of the problem, $F_{sp1-fail-st2}$ is finding that SP1 fails to satisfy State 2, $F_{sp111-satisfy-st1}$ is finding that SP111 satisfy State 1.

It can be observed from the above synthesis processes that multi-state design task is a step by step process. The need is abstracted to the level of specifying it as a multi-state design task, which is a set of states and state transitions. After analyzing the multi-state design task, a strategy is selected to generate an initial solution proposal(s). Three strategies of generating initial solution proposal(s) are observed. They are: (1) Choosing a state to generate initial solution proposal(s) either fully or partially satisfying that state (and keep it modifying for satisfying that state, if it does not satisfy fully) as done by the researcher, Designer1, Designer2, Designer3, Designer4, Designer5, Designer8 and Designer9; (2) Choosing a known pair or mechanism as done by Designer7 and Designer9 and (3) Generating initial solution proposal(s) independently componentwise for the input and output components by

Table 1. Example of coding activity.

Transcribed Speech	Transcribed Action	Input	Code of activity	Definition of Activity	Output
And then i see that all these condition is satisfied or not. That first condition is satisfying	evaluation for state1	SP111 & ST1	$E_{sp111\text{ - }st1}$	Evaluate sp111 against state1	$F_{sp111\text{-satisfy-}st1}$
and then I concentrate on the first state	selected state1 to start synthesis	P	S_{st1}	select state1	ST1/P
That is there is one torque is applied and the wedge translates inside. That is torque is converted into translational motion	analyed state1 for type, direction, axis of input effort,and type, direction, axis of associated motion and desired type, direction, axis of output motion and their associated elements	ST1/P	A_{st1}	Analyze state1	
Corresponding to this one, how much it will go in that I have to put a block here. This is for state2	he modified solution proposal1 by adding grounded obstruction	$F_{sp1\text{-fail-}st2}$	$M_{add\text{-}grounded\ obstruction}$	modify by adding grounded obstruction	SP11
The first thing that comes to mind is slider crank mechanism	he generated a slider crank mechanism(sp1) to satisfy rotation to translatory motion	ST1	G_{sp1}	Generate solution proposal1	SP1

considering only their motions, for all the states as done by Designer6. After generating the initial solution proposal(s), it is repeatedly evaluated and modified for each state to arrive at the final solution. The observed set of activities, ASGEM (analyse, select, generate, evaluate, modify) will be explored further in depth.

It can be observed that the solution(s) generated by each designer is different from the solutions generated by the other designers. This fortifies the need to have a support system, which can help each designer to generate a wide variety of solutions.

7. CONCLUSIONS

A representation of state for mechanical devices is proposed. An observational study of synthesis processes of a multiple-state mechanical device by ten individual designers is presented. A generic set of activities of synthesis of mechanical devices is identified.

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