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AN EMPIRICAL MODEL OF THE PROCESS OF SYNTHESIS OF MULTIPLE STATE MECHANICAL DEVICES

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ABSTRACT
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 based on the processes of synthesizing multiple state mechanical devices carried out individually by ten engineering designers. The designers are asked to think aloud, while carrying out the synthesis. The ten design synthesis processes are video recorded, and the records are transcribed and coded for identifying activities occurring in the synthesis processes, as well as for identifying the inputs to and outputs from the activities. A mathematical representation for specifying multi-state design task is proposed. Further, a descriptive model capturing all the ten synthesis processes is developed and presented in this paper. This will be used to identify the outstanding issues to be resolved before a system for supporting design synthesis of multiple state mechanical devices that is capable of creating a comprehensive variety of solution alternatives could be developed.

Keywords: Automated synthesis, multiple state, design, mechanical device

1 INTRODUCTION
The overall aim of this research is to develop a generic support system to help designers synthesize a wider variety of design alternatives than currently possible for multiple state mechanical devices during the conceptual phase of mechanical design. Mechanical design can be seen as a process of transforming a perceived need into a description of a physical structure that uses mechanical engineering principles to satisfy the need. In conceptual design, a functional requirement is transformed into the concept of a solution. Research into methods for automating the conceptual phase of the design process has attracted much attention in the past decades. Conceptual design has the most significant influence on the overall product cost [1], [2]. Conceptual design is a difficult task [3], [4], which relies on the designer's intuition and experience to guide the process. A major difficulty in this task is that many potential solutions are not considered by the designer during the design process [5], [6], [7]. The major causes for this difficulty are the tendency to delimit a design problem area too narrowly and thus not being able to diversify the possible set of design solutions, possible bias towards a limited set of ideas during the design process, and time constraint [8]. 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.
A mechanical device is a set of two or more relatively constrained components which may serve to transmit or modify force or motion so as to fulfill certain intended mechanical functions. Li [8] 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. Other researchers [9-12] defined state in other ways. Adapting the definition of Li [8], we define the state of a mechanical device as follows. Let there be a device with a set $L = \{L_1, L_2, L_3 \ldots\ldots L_m\}$ where L is the set of components from all the states of the device, which acted as either input components or output components. 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 a device has a set of configurations, C= {C_1, C_2, C_3… C_n}, where C_k = {a_1, a_2, a_3,...., a_m} and a_i 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 C_{pp} of L, due to a non-zero effort on some components of L. A state transition S_{pq} is defined as a change of state from C_{pr} to C_{rq}.

2 RESEARCH PLAN

The central question to be addressed in this research is – how to synthesize, automatically or interactively, a comprehensive set of possible device concepts that satisfy a given task comprising multiple states? The sub-questions are:

- How can multiple state design tasks and devices be represented?
- How can the functioning of multiple state mechanical devices be analyzed?
- How can a comprehensive set of multiple state devices be automatically or interactively synthesized?

The questions are to be addressed through the following: literature study, study of synthesis on multiple state design tasks done by the researcher, study of synthesis on multiple state design task 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 currently carried out by designers. A multiple state design task is specified using states and their transitions. Ten designers, including the researcher, are given a specific 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 synthesis processes and their outcomes. This understanding is used as a basis for developing the support.

3 LITERATURE STUDY

The research evidence suggests that a thorough exploration of solution space is more likely leads to designs of higher quality [13]. Li [8] used the concept of 'state' approach to mechanical devices and carried out his research on synthesis of single and multiple state mechanical devices. He used the configuration space approach to represent and retrieve the behavior of a kinematic pair and developed ADCS (Automatic Design by Configuration Space) for automatically generating solutions of mechanical devices satisfying single and multiple state design tasks. Many other researchers [14-31] attempted mechanical design synthesis through various approaches.

The approach of 'developing a knowledge model on the basis of the synthesis process of mechanical devices done engineering designers work' is adopted in this research work.

4 SELF STUDY ON MULTISTATE MECHANICAL DEVICESS

A multi-state door latch device is used as the case for analysis and its states and state transitions for synthesis. This section shows the results of the analyzing the video protocols of the researcher himself.

4.1 Analysis of multi-state mechanical device

An existing multi-state door latch is modeled as shown in Figure 1. The latch has an L-shaped handle hinged at A, a torsion 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. In State1, the handle is rotated by applying some torque from Θ=0 to Θ= Θ_1 and this rotation of the handle pulls the block simultaneously from X=0 to X= x_1. In State2, when the handle is at Θ= Θ_1 and the block at X= x_1 even if torque is continued to be applied, the handle and the block does not move. In State3, when the torque on the handle is released, the handle rotates from Θ= Θ_1 to Θ=0 and the block also moves from X= x_1 to X=0 simultaneously. In State4, when the handle is at Θ=0 and the block is at X=0, apply force on the block along negative X direction pushing the block inside to X= x_2, but there is no change in the orientation of the handle. In State5, when the handle is at X= x_2, release the force on the block, the block comes back to X=0. The initial and final configurations of the door latch device in each state and the state transitions are also explained in Figure 3.

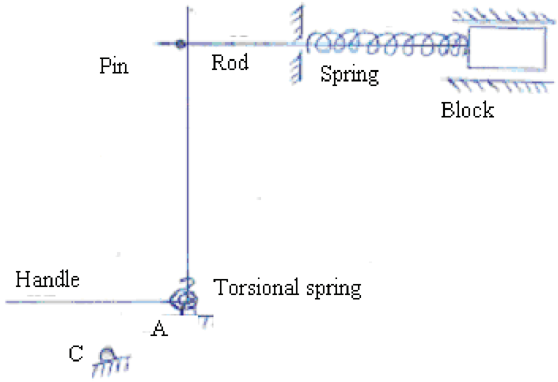


Figure 1. Model of the door latch

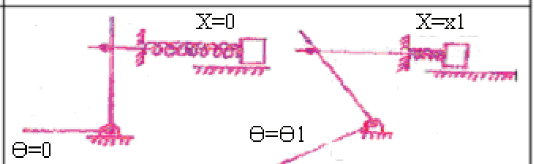
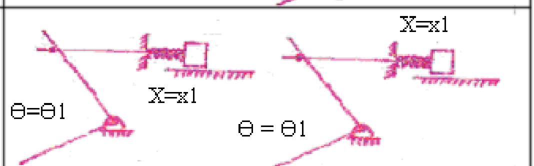
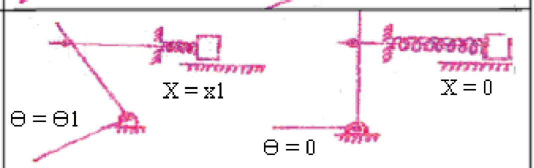
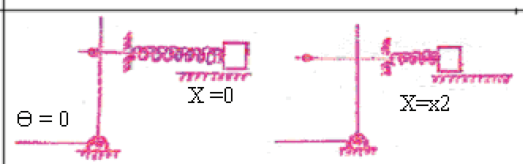
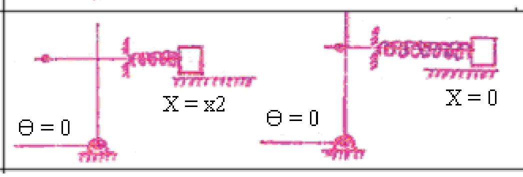
State description	Initial and final configurations in that State
In State1, when torque is applied on the handle,it rotates from Θ=0 to Θ=Θ1 and the block is pulled inside from X=0 to X=x1.	
In State2, when the handle is at Θ=Θ1 and the block is at X=x1, keep applying torque on the handle, handle doesn't move and the block also	
In State3, when the handle is at Θ=Θ1 and the block is at X=x1, release the torque on the handle, handle rotates back to Θ=0 and the block	
In State4, when the handle is at Θ=0 and the block is at X=0, apply force on the block, it moves inside to X=x2 and the handle remains at Θ=0.	
In State5, when the handle is at Θ=0 and the block at X=x2 , release the force on the block, it moves to X=0 and the handle remains at Θ=0	

Figure 2. Explanation of States of the five state door latch through the model of the door latch

From the above analysis of the device, its design problem can be formulated as a five state design task. If the handle and the block are considered as two components as L_1 and L_2 respectively, which act as input or output components in different states. L_1 and L_2 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 $C_1 = (0, 0)$, $C_2 = (\Theta_1, x_1)$ and $C_3 = (0, x_2)$. Now the behavior of the five state latch be represented as a set of states and state transitions, where State1 is a change in configuration from C_1 to C_2 of L, due to a torque on L_1, State2 is no change in configuration C_2 of L, due to a non-zero torque on L_1, State3 is a change in configuration C_2 to C_1 of L, due to release of torque on L_1, State4 is a change in configuration C_1 to C_3 of L, due to a force on L_2 and State5 is a change in configuration, C_3 to C_1 of L due to release of force on L_2.

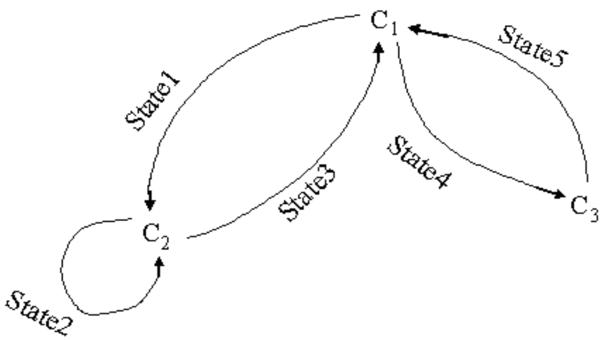


Figure 3. Solution proposals generated by the researcher at different stages of the synthesis process

4.1.1 Mathematical representation for multi-state design task

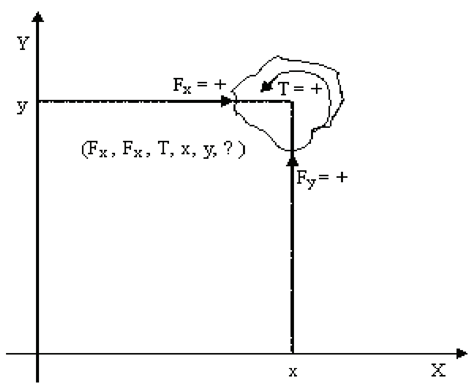


Figure 4. Configuration of a component in plane motion

A mathematical representation for a multiple state design task is proposed as follows. A state is represented with respect to a configuration change and the effort involved in bringing about that configuration change. If two dimensional devices are considered, configuration of a body can be specified by a vector of three parameters(x, y, Θ) and effort, which can be force or torque, is specified by a vector of three parameters(F_x, F_y, T). So a six parameter vector (F_x, F_y, T, x, y, Θ) can be used to represent an effort on a component and configuration at which the effort is applied. Each of Fx, Fy and T can take values +,0,-. F_x = + means that force is applied along positive direction of X- axis. F_x = – means force along negative direction of X- axis. F_x = 0 means no force no force is applied along X-axis and so as the values for F_y can be interpreted in similar. T= + means torque along positive Z-axis in the direction of curling of fingers when thumb is pointing positive Z-axis. T=0 means no toque is applied along Z-axis. T= - means torque applied in reverse direction to the curling of right hand fingers, when the right hand thumb pointing positive Z –axis direction as shown in Figure 4.

So adapting the definition of state of a device as the change of configuration of the device induced by an associated effort, or no change of configuration for a non-zero effort, a six parameter vector can be used to represent effort and the configuration of any component of the device in plane motion as (F_x, F_y, T, x, y, Θ). The first three parameters represent the effort, while the next three represent the configuration. For example, when a component is at the configuration (x_1, y_1, Θ_1) and a force (+,0,0) is applied on the component to bring it to another configuration (x11, y1, Θ1), this can be represented as: ((+,0,0, x_1, y_1,0), (+,0,0, x_{11}, y_1,0)). So, 12 parameters are required for specifying the change in configuration of each component. For a device, which has a set of 'n' components acting as input or output components, there will be 12n parameters to represent the state of the device. Basic configuration of a device is the configuration of the device when no external effort is applied on it. A multi-state design task can have more than one basic configuration, and can have more than one state which starts from basic configurations. Using the above mathematical representation, the multi-state door latch design task, which has two components acting as input or output components, can be represented as follows:

Basic configuratión: ((0,0,0, x_1, y_1,0), (0,0,0, x_2, y_2,0), (0,0,0, x_1, y_1,0), (0,0,0, x_2 , y_2,0)).
State1: ((0,0,+, x_1, y_1,0), (0,0,0, x_2, y_2,0), (0,0,+, x_1, y_1,Θ_1), (0,0,0, x_{22}, y_2,0)).
State2: ((0,0,+, x_1, y_1,Θ_1), (0,0,0, x_{22}, y_2,0), (0,0,+, x_1, y_1,Θ_1), (0,0,0, x_{22}, y_2,0)).
State3: ((0,0,0, x_1, y_1,Θ_1), (0,0,0, x_{22}, y_2,0), (0,0,0, x_1, y_1,0), (0,0,0, x_2, y_2,0)).
State4: ((0,0,0, x_1, y_1,0), (-,0,0, x_2, y_2,0), (0,0,0, x_1, y_1,0), (0,0,-, x_{222}, y_2,0)).
State5: ((0,0,0, x_1, y_1,0), (0,0,0, x_{222}, y_2,0), (0,0,0, x_1, y_1,0), (0,0,0, x_2, y_2,0)).

4.2 Synthesis of solutions for the multi-state door latch design task

The five state design task devised from the analysis of the door latch device is taken up here as a problem to solve by synthesizing solutions by the researcher.

After analyzing the given five state design task, State1 was selected to focus on and rack and pinion, slider crank mechanism, rope and drum and cam and follower were generated as potential solutions to satisfy this state, see Figure 5(a)-(d). Four handles were generated as shown in Figure 5(e)-(h) for applying torque by the hand. These handles were evaluated and it was found that two, shown in Figure 5(g) and Figure 5(h) were better suited; the other two were rejected. The four mechanisms, shown in Figure 5(a)-(d), were evaluated against State1. Cam and follower, shown in Figure 5(d), failed to satisfy axis transition requirement of State1. So It was modified producing two alternatives as shown in Figure 5(i) and Figure 5(j). Three possible joints shown in Figure 5(k)–(m) were generated to connect between the two selected handles, Figure 5(g)-(h), and five mechanisms (Figure 5(a)- (c) and Figure 5(i)- (j)). So two handles, three joints and five mechanisms are combined to produce 30(=2*3*5) alternatives for satisfying State1. Next State2 was selected and three arrangements shown in Figure 5(n)–(p)) were generated to satisfy both State1 and State2 as they could be rotated certain angle and stopped. So 90(=2*3*5*3) alternatives for satisfying State1 and State2 were generated. Next State3 was selected and a torsional spring was generated for State3, and all the 90 alternatives were modified by adding the torsional spring. All the 90 were evaluated for State1-State3. The 18(=2*3*1*3) alternatives that use rope and drum shown in Figure 5(c) did not satisfy State3. These 18 were modified by removing torsional spring and adding a tensile or compression spring, producing 36(=2*3*1*3*2) alternatives using drum and rope. Two of these 36 were shown in Figure 5(q)-(r). All these 108(= (2*3*4*3)+(2*3*1*3*2)) alternatives, which satisfied State1- State3 were evaluated for State4. All except the 36 alternatives that use rope and drum and 18(2*3*1*3*1) alternatives that use cam and follower shown in Figure 5(j) failed to satisfy State4. So 54(=108-36-18) alternatives could satisfy State1-State3 but failed State4 and 54 alternatives satisfied State1- State4. So one new block, to act as an input or output element, was added to 54 alternatives which failed State4. a new four state design task between two blocks was formulated from the State1- State4 of the original five state design task. Four alternatives were generated as shown in Figure 5(s) – (v) for satisfying newly formulated four state design task. These four were integrated into the 54 mechanisms, which satisfied State1-State3 but not State4, generating 216(=54*4) alternatives. So 270 (=18+ 36+ (54*4)) alternatives satisfied State 1- State4. All these 270 were evaluated for State5 and satisfy State5. So 270 solutions were synthesized, which satisfied all the five states. One of those 270 alternatives formed from Figure 5(a), (g), (k),(p) and (t) is shown in Figure 5(w).

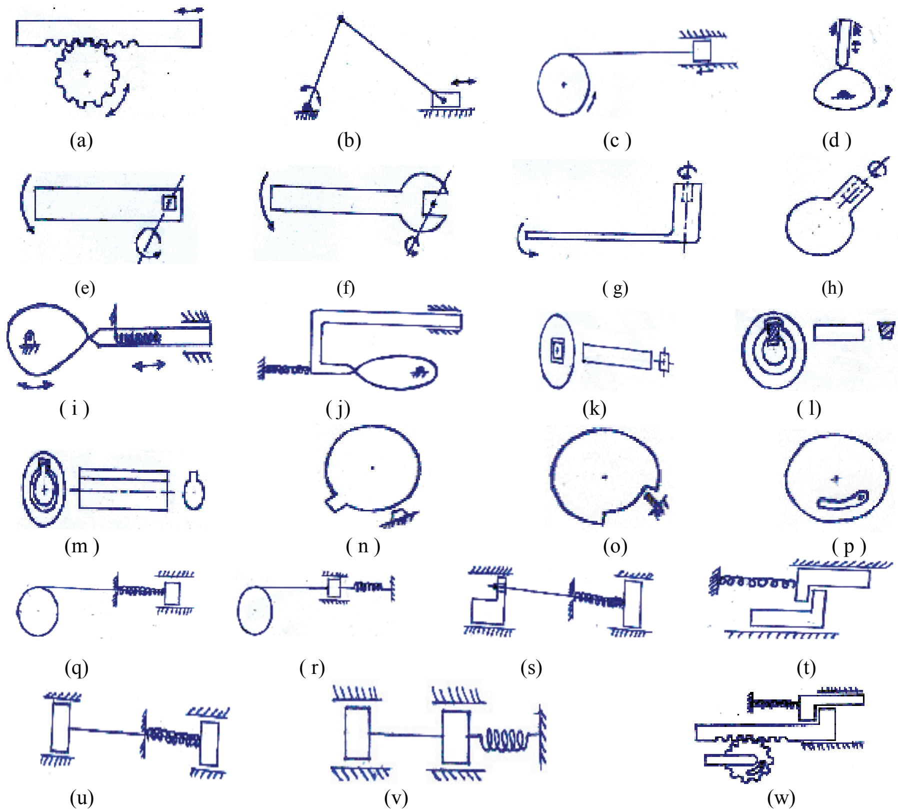


Figure 5. Solution proposals generated by the researcher at different stages of the synthesis process

5 STUDY OF SYNTHESIS DONE BY NINE OTHER DESIGNERS

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

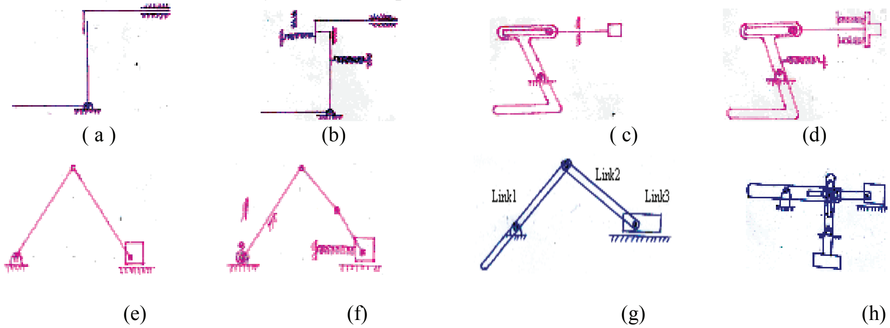


Figure 6. Example of figure Initial solution proposals and final solutions generated by Designer1, Designer2, Designer3 and Designer4

Designer1 selected State1, generated the solution proposal shown in Figure 6(a) for State1, modified it by adding a grounded obstruction for State2 and a linear spring for State3, evaluated it against State4 and State5 and found that all states were satisfied and arrived at the solution shown in Figure 6(b).

Designer2 selected State1, generated the proposal shown in Figure 6(c) and modified it by adding a grounded obstruction for State2, and springs for State3. He evaluated it against State4 and State5. As they were satisfied and solution was generated as in Figure 6(d).

Designer3 selected a two step strategy. In Step1, he generated a proposal to convert rotary motion of Component1 to translatory motion of Component2 and translatory motion of Component2 to rotary motion of Component1. In Step2, he modified the proposal such that rotary motion of Component1 gives translatory motion of Component2 and translatory motion of Component2 does not give rotary motion of Component1. He generated a slider crank mechanism shown in Figure 6(e) for Step1 and modified it by adding grounded obstruction near the crank for State2. He modified again by adding a torsional spring and linear spring for State3 and replaced the connecting rod with two links connected by a hinge for Step2. His finally synthesized is solution shown in Figure 6(f).

Designer4 generated a slider crank mechanism as shown in Figure 6(g) for State1 and modified it by adding Link4 for State2. He modified the crank (Link1) with a slot for State1 and State2, a slot in and a mass to Link4 for State3. For State4, he modified the alignment of Link1 and 2. This also satisfied State5 and solution was arrived as in Figure 6(h).

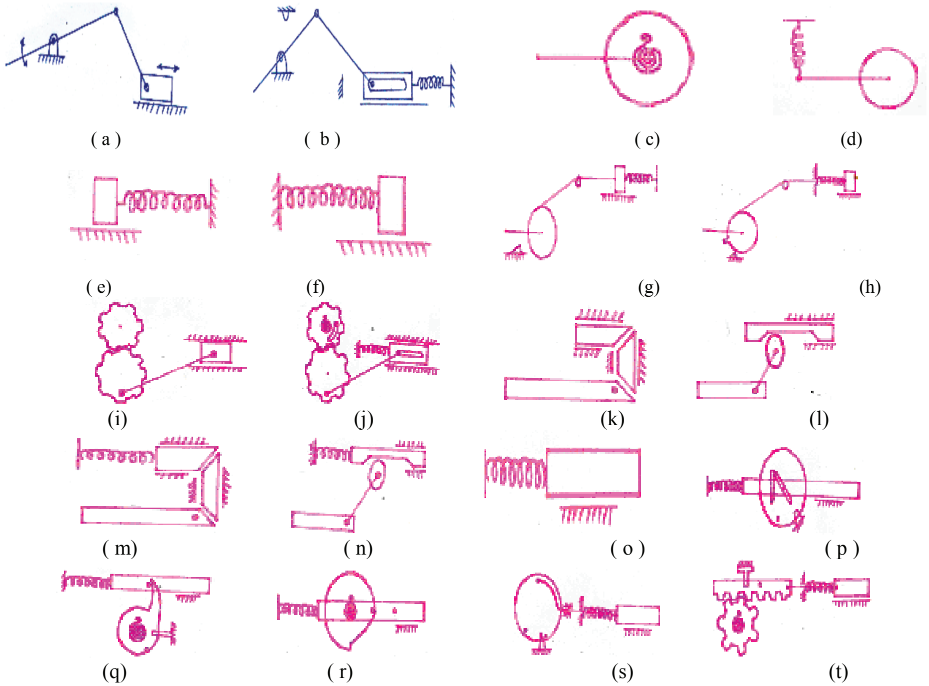


Figure 7. Initial solution proposal and final solution synthesis done by Designer5, Designer6, Designer7, Designer8 and Designer9

Designer5 generated a slider-crank mechanism as in Figure 7(a) for State1. He modified it by adding a grounded obstruction for State2, a linear spring to the slider for State3 and a slot in the slider for State4. As State5 was also satisfied, a final solution was synthesized as shown in Figure 7(b).

Designer6 generated two alternatives, Figure 7(c)-(d), for Component1 motions and the two alternatives, Figure 7(e)-(f) for Component2 motions, from all the states. For State1, he joined these with a rope to produce four alternatives. For State2, he modified the disk shape and added a grounded obstruction. Two of the alternatives are shown in Figure 7(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 State1 as shown in Figure 7(i). He modified the gear shape with a slot and a pin in the slot for State2 and added a torsional spring for State3. For State4, the follower was kept in a cylindrical shaped component. As this modification

failed State3, he modified it by adding a linear spring. As State4 and State5 were also satisfied, final solution was arrived at as shown in Figure 7(j).
Designer8 selected State1 and generated two proposals as shown in Figure 7(m)-(n). He modified these by adding a grounded obstruction for State2 and springs for State3, and evaluated these for State4- State5. As they were satisfied, he arrived at two solutions as shown in Figure 7(k)-(l)
Designer9 selected the strategy of generating a solution proposal for State4 and State5 and modifying it for State1- State3. He generated a solution proposal as shown in Figure 7(o). For State1, he modified the proposal by adding projections on it and adding a circular disk, which also had a projection on it. For State3, a torsional spring was added to the circular disk. State4 and State5 were evaluated and found to be satisfied. His solution is shown in Figure 7(p). For State4 and State5, he again started with the proposal in Figure 7(o) and modified it for State1-State3 as shown in Figure 7(p). He again selected a strategy to develop a solution using the concept of cam profile. For State4 and 5, he used the proposal in Figure 7(o) and modified it for State1-State3, as shown in Figure 7(r). He selected a strategy to develop a solution using a flexible element like string. He synthesized two solutions as shown in Figure 7(s)-(t).

6 OBSERVATIONS FROM THE ABOVE SYNTHESIS PROCESSES

It can be observed from the above synthesis processes that multi-state design task is a step by step process. Each designer was able to generate one or few solutions. Another key observation is that the set of solutions generated by each designer is different that generated by the other designers. This means that none of the designers is able to generate a comprehensive set of solutions. The time taken by each designer was also considerably high. These fortify the need to have a support system that can capture a wider set of solutions than what any single designer is able to generate.

7 CODING

From the transcriptions of the ten videos of the synthesis processes, coding [32] is through identification of the following elements from the video: transcribed speech, transcribed action, input to activity, code of activity, definition of the code, output of the activity. Transcribed speech is what the designer speaks out in think-aloud; transcribed action is used whenever the designer did some work and forgot to think-aloud while carrying out his synthesis process. Input is about what was considered for doing an activity; the resultant of the activity is taken as output. An example result of coding is shown in Table 1. *Analyze*, *Select*, *Generate*, *Evaluate* and *Modify* are identified as the five primary level activities that are observed to occur in the synthesis processes. *Analyze* is to consider something in detail in order to discover its essential features. *Select* is to choose something from a number of alternatives. *Generate* is to produce something. *Generate* has three secondary level activities: *List*, *Retrieve* and *Derive*. *List* is to form a set with things. *Retrieve* is to bring back something from memory; *derive* is to deduce from something. *Evaluate* is to compare something with respect to some other thing. *Modify* is to change something. *Modify* has several secondary activities: *Add*, *Replace*, and *Incorporate*. *Add* is to combine something with existing things. *Replace* is to substitute a thing for another. *Incorporate* is to merge something with some other thing already in existence.
The nomenclature is as follows: SP111 is solution proposal 111(SP1 is the initial solution proposal. SP11 is the resulting solution proposal after SP1 is modified. SP111 is the resulting solution proposal after modifying SP11. If modification of SP1 resulted in three varieties of solution proposals, then the resulting solution proposals are designated as SP11, SP12, and SP13). ST1 is State1, P is the given multi-state design problem, ST1/P is State1 of the problem; $F_{sp1\text{-}fail\text{-}st2}$ is finding that SP1 fails to satisfy State2, $F_{sp111\text{-}satisfy\text{-}st1}$ is finding that SP111 satisfy State1, and $LI1_{SP111111}$ is list1, which has SP111111 as its element.

8 A COMMON DESCRIPTIVE MODEL

From above the coding process and subsequent analysis of the codes and their sequences, a common superimposed descriptive mode is proposed as shown in Figure 8.
From the need, functions that need to be performed by the device are established. From these functions, states and state transitions are identified, resulting in the framing of the multi- state design task. After analyzing the multi-state design task, a strategy is selected to generate a set of initial solution proposals. Three strategies of generating the set of initial solution proposals are observed.

These are: (1) Choose a state, S_i that is linked to a basic configuration. and generate a set of initial solution proposals either fully or partially satisfying that state (and keep modifying the initial solution proposals till they satisfy that state fully), as found to have been followed by the researcher, Designer1, Designer2, Designer3, Designer4, Designer5, Designer8 and Designer9; (2) Choose a component, pair or mechanism and develop an initial solution proposal from the chosen component, pair or mechanism for any state S_i that starts from a basic configuration, as followed by Designer7 and Designer9 and (3) Choose one state and generate proposals for each of the input or components individually for that state, select the next state and modify these proposals of components and keep on

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	$F_{sp111\text{-}satisfy\text{-}st1}$
Finally met the solution	he generated list1 with the solution proposal111111	SP111111	$G_{LI1\text{ - }sp111111}$	generate list1 with sp111111	$LI1_{SP111111}$
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	analyzed 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	$F_{sp1\text{-}fail\text{-}st2}$	$M_{add\text{-}grounded\ obstruction}$	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

modifying these proposals for components individually for all the remaining states. Now select any state Si, which starts from basic configuration and modify by connecting the above generated component solutions in a suitable manner to satisfy Si and this becomes initial solution proposal. This strategy is used by the Designer6. After generating a set of initial solution proposals, it is repeatedly evaluated and modified for each state to arrive at the final solution.

The modification activity is explained in Figure 9. Modification activity is a cyclic process. It has a solution proposal and a set of requirements specified in the state of focus as inputs. The proposal has to be evaluated, unsatisfied requirements identified; proposals generated for fulfilling the unsatisfied required on the given solution proposals. The modified solution proposals are again evaluated, to check and ensure that no unsatisfied requirement exists or no requirement satisfied earlier is negated by the modification. This cycle of activities repeats till all the requirements are satisfied.

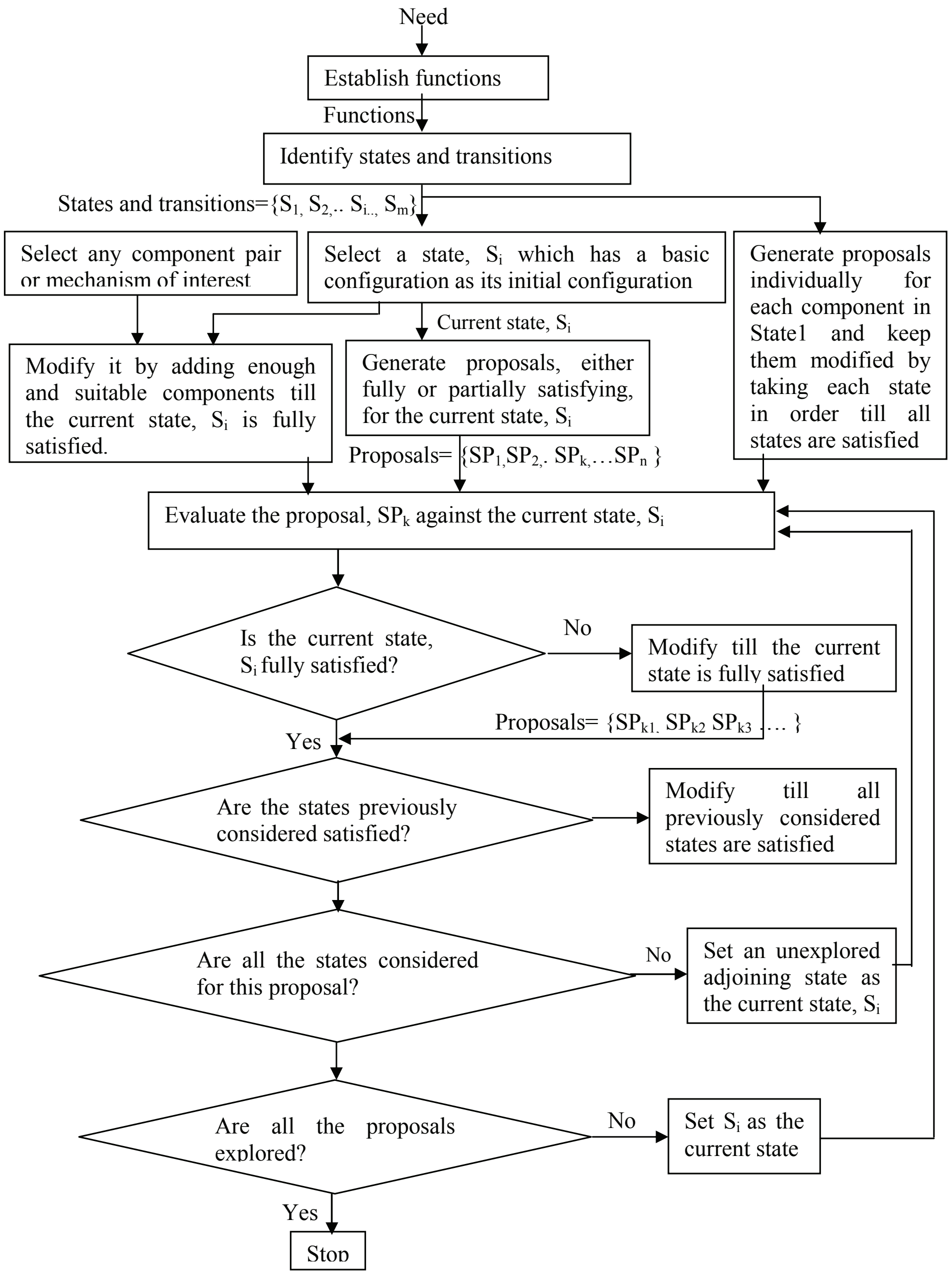


Figure 8. Common descriptive model

9 CONCLUSIONS AND FUTURE WORK

A representation of the state for a mechanical device and a multiple state design task are proposed. An observational study of synthesis processes of a multiple-state mechanical device by ten individual designers is presented. A common descriptive model capturing all the ten synthesis processes is proposed. A generic set of activities and outcomes of the process of synthesis of mechanical devices is identified. These activities will be explored in depth for possible levels of automation or support.

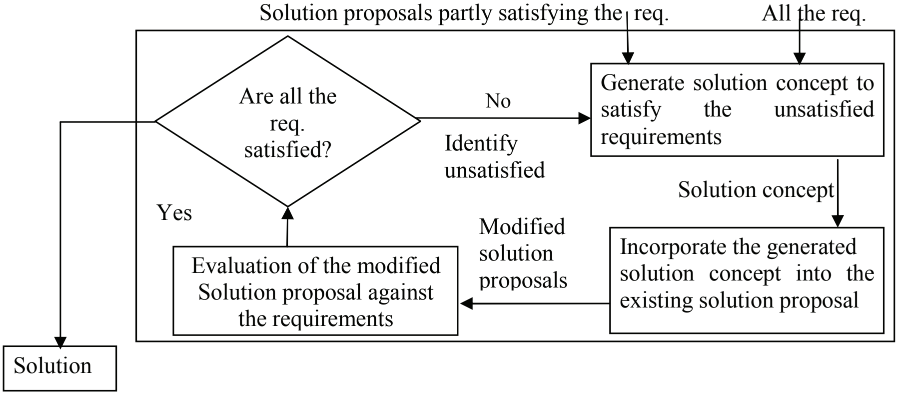


Figure 9. Modification activity

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