AN EMPIRICAL STUDY OF SYNTHESIS OF MULTIPLE STATE DEVICES BY ENGINEERING DESIGNERS

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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 an empirical study of the process of synthesis of multiple state mechanical devices. As a background to the work, the paper explores concepts of what mechanical device, state, single state and multiple state are, and in the context of the above observational studies, attempts to identify the outstanding issues for supporting multiple state synthesis of mechanical devices.

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 a 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 not many potential solutions are 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.

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?
- 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 first author
- Study of synthesis done by other designers
- Development of support for progressive automation of the synthesis process for multiple state design tasks
- Evaluation of the support.

3 Literature Study

A mechanical device is a set of two or more relatively constrained parts which may serve to transmit or modify force or motion so as to fulfil certain intended mechanical functions.

The operating state [8] of a device is characterized by a set of relations between its input and output motions. The set of relations is valid and 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], [10], [11], 12] defined operating state (hence forth referred to as state) in various other ways. The stated in Li [8] are taken as initial basis and considered for further exploration in this research work, see section 4.1.2.

The research work on synthesis of multiple state mechanical devices has been carried out primarily by Li et al. [8], [13], [14]. They have used the 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 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

4.1 Analysis of Multiple State Mechanical Device

The approach here is to analyze various existing multiple state mechanical devices for their structure, behaviour and function. How the combination of various elements and pairs contributes to the functioning and behaviour of the structure is observed. States and state transitions of mechanical device are identified. Here a door latch problem is used as the case for analysis.

4.1.1 Modeling of Door Latch

The door latch is modelled as shown in Fig. (1). The model contains an L-shaped handle hinged at A, a torsional spring connected to the handle at the hinge A, a wedge, a rod attached to the wedge and a spring arrangement, a small pin attached to the rod protruding in the perpendicular direction to the plan of the paper.

4.1.2 Representation of a State

Using the definition of Li [8] as basis, we define the following as a state of a mechanical device. Let there be a device which has a set of elements, $L=\{L_1,L_2,L_3\ldots L_m\}$ as input or output elements. The elements on which we apply

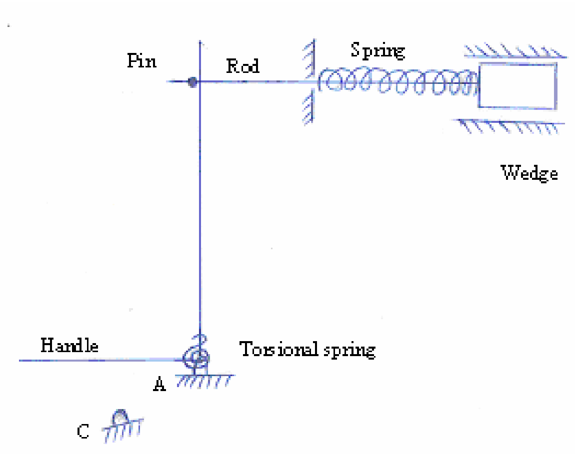


Figure 1: Model of door latch.

an effort are termed as input elements. The elements for which we observe the final outcome of the effort are termed here as output elements. The set of elements, L, of a device has a set of configurations, $C=\{C_1,C_2,C_3\ldots C_n\}$, where $C_k = \{a_1, a_2, a_3,\ldots,a_m\}$ and a_i is the configuration (position or orientation) of L_i. Now the behaviour of the device can be summarized as a set of states and state transitions, where a state(S_p) can be a change in configuration, C_{pq} (Cp to Cq) of L, due an effort on some elements of L, or no change in configuration C_{pp} of L, due to a non-zero effort on some elements of L. A state transition S_{pq} is be defined as a change of state from C_{pr} to C_{rq}.

A simplified diagrammatic representation of a state of a device which contains $L=\{L_1,L_2\}$ as a set of two of its elements and configuration set, $C=\{C_1, C_2\}$,where $C_k=\{a_1,a_2\}$ and $C_k=\{b_1,b_2\}$. By the application

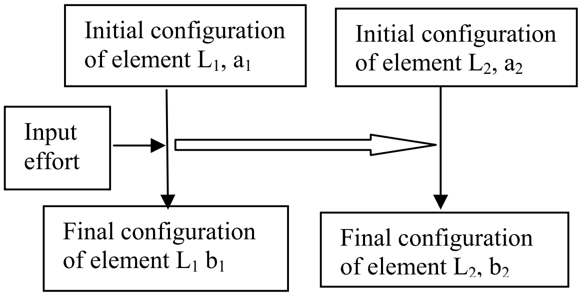


Figure 2: Representation of a State

of an input effort on element L_1, its configuration changes from an initial configuration, a_1 to a final configuration, b_1. This configuration change of element L_1 causes a change in the configuration of element L_2, from its initial configuration, a_2 to its final configuration, b_2 is shown in Fig. (2).

Local coordinate frames are fixed to the handle and the wedge as shown in Fig. (3). The following convention is used for the direction of rotation along an axis, right hand thumb along it's + direction and the direction of curling of right hand fingers is considered as anti-clockwise direction.

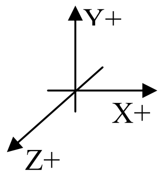


Fig. 3: Representation of coordinate system

If the behaviour of the door latch device is analyzed and divided into states, it would contain the following five states as diagrammatically represented in Fig. (4).

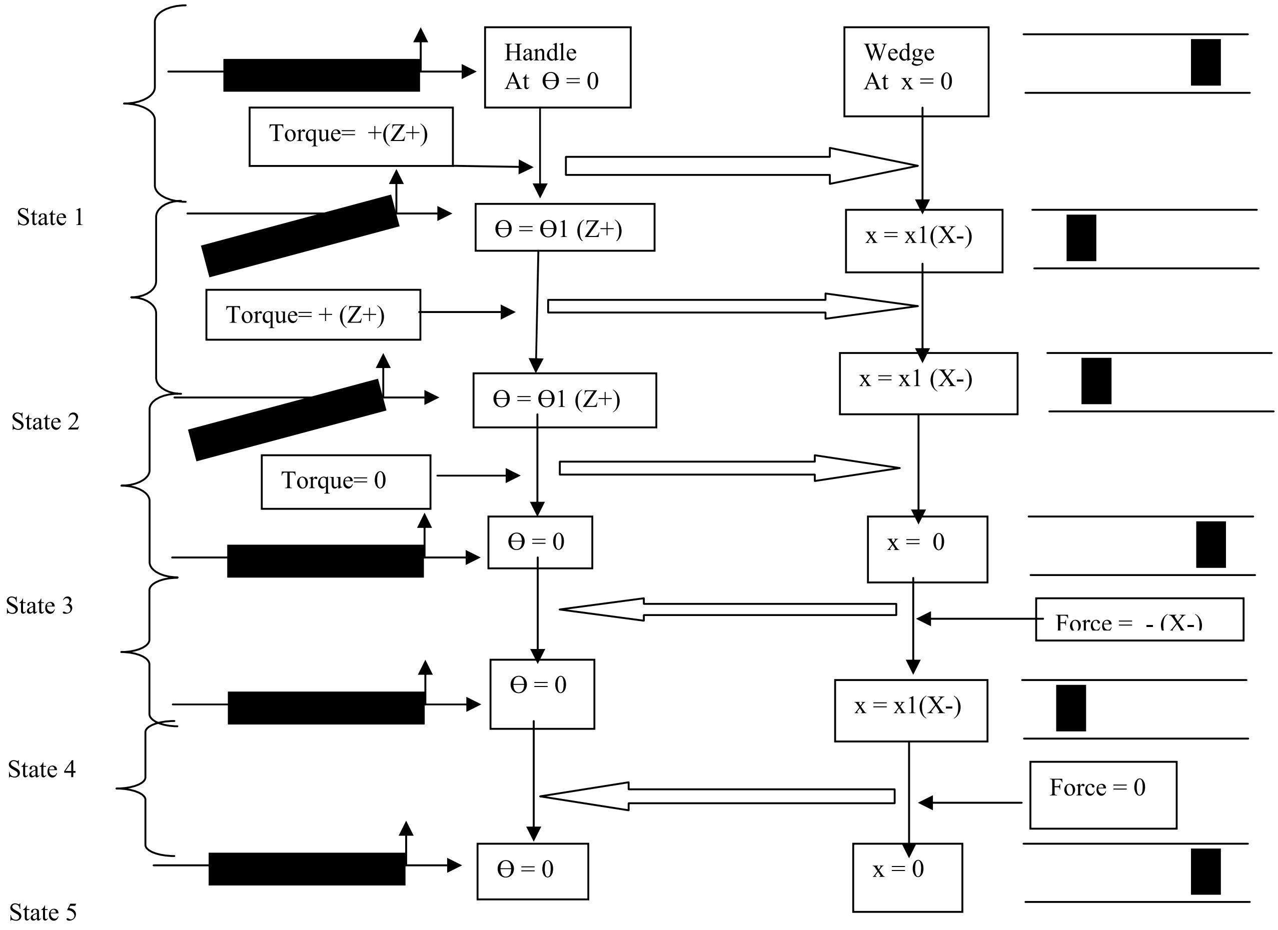


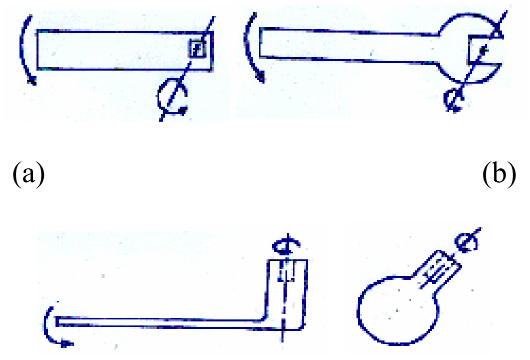
Figure 4: States and state transition of door latch

Let us fix motion parameters to the handle and the wedge as Θ and x respectively. If the L- shaped handle is rotated from Θ =0 to Θ = Θ1 by applying torque, then it pulls the wedge inside from x = 0 to x = x1, by compressing the spring. Let us call this as *State1*. When the handle is at the position, Θ = Θ1, even if torque is applied to rotate it in the same direction, it doesn't rotate further due to blockage by the obstacle kept at C, which is fixed to the frame and consequently the wedge remains at the same position, x=x1. Let us call this as *State2.* Now if the torque on the handle is released, when it is at Θ = Θ1, then it comes back to its original position, Θ =0 because the torsional spring at hinge A pulls the handle back; simultaneously, the wedge goes back from x= x1 to x= 0 due to the spring force. Let us call this as *State3*. Now if a force is applied on the wedge, when it is at x = 0, then it translates inward, and the handle (at Θ = 0) doesn't get affected. Let us call this as *State4*. If the force applied on the wedge is released now, then it comes back to its original position, x=0 due to the spring force, without affecting the position of the handle, at Θ = 0. Let us call this state as *Stat 5*.

4.2 Synthesis of Multiple State Mechanical Devices

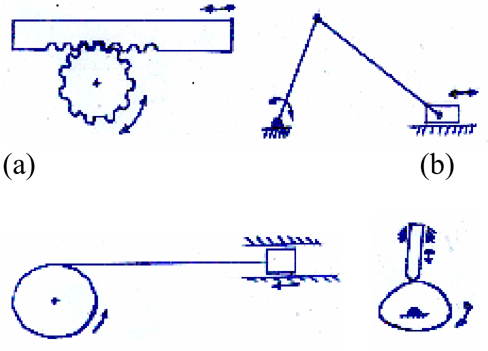
Various multiple state devices are synthesized by the authors for developing alternative designs for the above multi-state function, the process undergone is reflected up to to understand the approach to designing such devices. This task is video recorded. Think aloud protocol is followed while doing the synthesis. The process and outcome of the synthesis of solution alternatives for the door latch problem is explained below. The states and state transitions diagram shown in Fig. (4) from the analysis of door latch device, is used as the device function in the synthesis process.

State1 requirement says that the handle should rotate from $\Theta = 0$ to $\Theta = 01$ when torque is applied on it. So the transition required is from torque on the handle to rotation of the handle and to translation of the wedge. For converting torque to rotation four alternatives are generated as shown in Fig. (5). The arrangements shown in Fig. (5(c)) and Fig. (5(d)) are selected from those four as they provide better handling. For converting rotation to translation, the alternatives generated are as shown in Fig. (6). These are evaluated. It is found that the cam and follower arrangement shown in Fig. (6(d)) fails to satisfy axis requirement of State1. The axis of the follower should be horizontal. So the follower is turned horizontal. To keep contact between cam and follower, a spring is used. This modification helps to generation of two alternatives as shown in Fig. (7). These two alternatives are evaluated and found that both satisfy requirements. Now these two solution alternatives are integrated to obtain final State1 solution alternative.


(a) (b)

(c) (d)

Figure 5: Various arrangements to convert torque to rotation.


(a) (b)

(c) (d)

Figure 6: Various arrangements to convert rotation to translation; a: Rack- pinion, b: Slider crank, c: Drum- rope, d: Cam and follower.

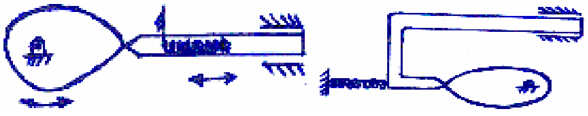

(a) (b)

Figure 7: Modified cam and follower arrangement.

As the joint between the handle (from the selected alternatives of Fig.(5)) and the element(from the mechanisms of Fig.(6))) that has to be integrated with the handle involves rotational arresting, three rotational arresting joints are generated as shown in Fig. (8). With the combination of Fig. (5(c)) and Fig. (5(d)), Fig. (6(a)), Fig. (6(b)), Fig. (6(c)) and Fig. (7) and Fig. (8), there are 2x5x3 i.e. 30 different alternatives are synthesized for State1.

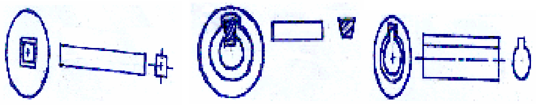


Figure 8: Various rotational arresting joints; a: square rod, b: key-slot, c: rod with projection

Now State2 requirement says that once the handle reaches to $\Theta = \Theta 1$, even if torque is applied to rotate it further in the same direction, it doesn't rotate and remains at $\Theta = \Theta 1$,also the wedge remains at x=x1. So one way of doing is by keeping an obstruction to the handle or to any coupling element, which is rotationally arrested with the handle at the required instant. If State1 and State2 requirements are super imposed, three alternatives are generated as shown in Fig. (9). So 30x3 i.e. 90 solution variants are synthesized till State2.


(a) (b) (c)

Figure 9: Various arrangements for blockage of motion after rotating to certain angle.

State3 requirement says that if the handle at $\Theta = \Theta 1$ is left free, it should rotate back to $\Theta = 0$ and wedge should translate from x=x1 to x=0 simultaneously. Springs can be used for this. As the motion involved is rotational, a torsional spring is used. It is evaluated for State3 requirements. All alternatives satisfy these except the arrangement in Fig. (6(c)). The arrangement in Fig. (6(c)) failed because the rope can not push the wedge back. So a linear spring is tried for this. Two ways of connecting this spring to the wedge as shown in Fig. (10). For arrangements in Fig. (10), torsional spring is redundant now and is removed. So 36 alternatives of drum and rope arrangements of Fig. (10) and 82 alternatives from other alternatives satisfy State3, State2 and State1 requirements. So 108 alternatives are synthesized till State3.

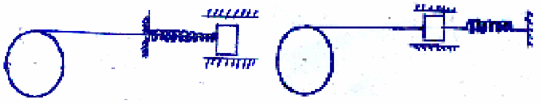

(a) (b)

Figure 10: Drum and rope arrangement of Fig. (6(d)) modified with spring connection to satisfy state3 requirement.

State4 requirement says that if force is applied on the wedge, which is at x=0, it translates inside without any change in the position of the handle, which is at $\Theta = 0$. As the element on which effort is applied changes from the handle to the wedge, all the varieties developed till now are evaluated for satisfying state4 requirements and modified to satisfy State4 requirements. As State4 requirements are imposed on all the developed varieties, 36 alternatives of drum and rope arrangements, shown in Fig. (10), 18 arrangements of cam and follower, shown in Fig. (7(b)) satisfy the requirements and the rest fail. Now modification is needed to be done to them. To prevent force getting transferred to the handle, the present wedge is assumed to be a dummy wedge, one more wedge besides this is created and connect the two to satisfy all the state requirements of State4, State3, State2 and State1. By working like this, four alternatives are generated as shown in Fig. (11). So 270 alternatives are synthesized till State4. When State5 requirement is applied on all of them, they are found to satisfy the requirements. So in total 270 varieties of solutions are synthesized satisfying all the states.

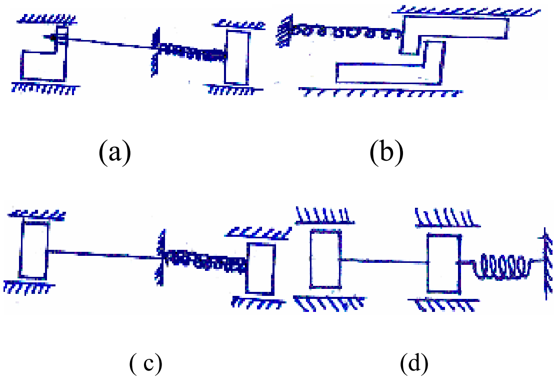


Figure 11: Various arrangements of wedges to satisfy State4, State3, State2 and State1 requirements. Rope is used to connect the wedges in (c) and (d) arrangements.

5 Study of Other Designers

In this case, ten experienced designers were given the above multiple state device design task and asked to develop as many solutions as they could to satisfy this multi-state door latch design task. No time constraint was imposed. The designers were asked to think aloud. This process was video recorded. These video records were analyzed to understand the process of synthesis in greater detail and variety, and provide a basis for supporting the synthesis process at the various levels of automation. Here the synthesis processes for the door latch problem done by two of the designers are described.

5.1 Study of Designer 1

The designer looked at the motion transition i.e. the input and out motions of state1, and generated a slider- crank mechanism, which can transform rotational motion to translational motion. Later he extended the length of the crank to provide handling function and named the links as link 1(crank), link 2 (connecting rod), and link 3(slider) as shown in Fig. (12). He evaluated the mechanism for State1 requirements. As it is satisfied, he proceeded to State2, and thought of two ways of obstructing the motion; one is by providing a stopper and other by proving an extra link. He chose to use the option of providing an extra link and named it as link 4, which has one end fixed to ground as shown in Fig. (13). Later he evaluated for State2, and State1 requirements. As it failed State1 requirement, he modified the crank with a slot in it as shown in Fig. (13). Later he evaluated the proposal for State1 and State2 requirements. As these are satisfied, he proceeded to State3, since it is required for the crank and slider to return to their original positions simultaneously, he thought of the option of using automatic release of potential energy, which could either be stored in spring or in a mass. He selected to use the gravitational potential energy in a mass at a height. He modified link 4 by extending its length at its hinged end and added a mass at its end as shown in Fig. (14). Now he evaluated this mechanism for State3. As these are satisfied, he proceeded to State4. He evaluated for state4 requirements and it failed due to rotation of crank when slider is pushed inside, he modified the solution by providing a slot in link 4 as shown in Fig. (15). Again he evaluated and found that it still failed. Now he modified the alignment of link 1, link 2, and slider. He aligned all three in a horizon-

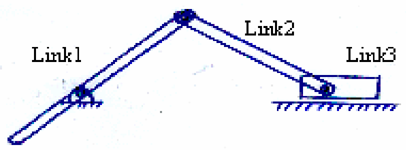


Figure 12: State1 solution synthesized by Designer 1.

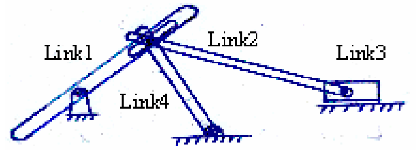


Figure 13: State2 solution synthesized by Designer 1.

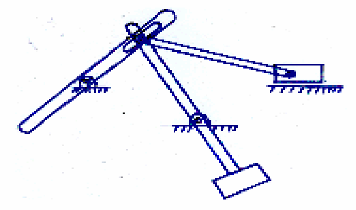


Figure 14: State3 solution synthesized by Designer 1.

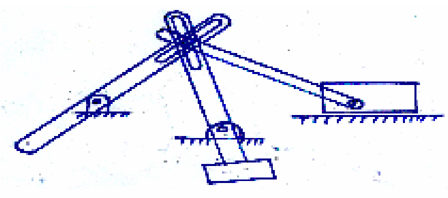


Figure 15: State4 solution synthesized by Designer 1.

tal straight line as shown in Fig. (16) such that when a force is applied on the slider, it pushes link 2 in the slot of link 1. Since this leads to no change in the position of link 1,it satisfied State4 requirements. So he evaluated the mechanism for State5, which was done by releasing the force on the slider. The slider comes back because the potential energy stored in the mass is released. So State5 requirement is also satisfied. All states requirements are evaluated again.

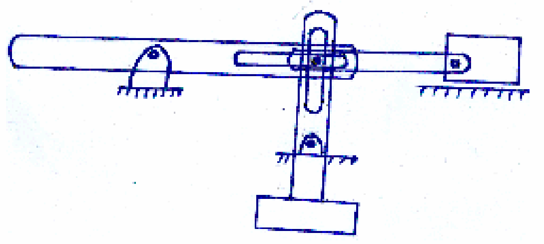


Figure 16: All states solution synthesized by Designer 1.

5.2 Study of Designer 2

The designer analyzed all the states and started with State1, which has motion transition from rotation to translation. He extended the length of the crank to provide the function of handling as shown in Fig. (17). He evaluated the mechanism for State1 requirement. Since it is satisfied, he selected the mechanism and kept it modifying it as he went on synthesizing for the other states. Now he applied State1 requirements on the mechanism to get the configuration change of the mechanism, which makes the crank to move to Θ1 position and slider to x1 position. Now he looked into State2 requirements, and generated an obstruction at Θ1, preventing the crank from rotating beyond Θ1 as shown in Fig. (18). As this satisfied State2 requirements, he evaluated for State1 as well. As State1 and State2 were satisfied, he proceeded to State3 requirements. As the crank and slider need to come back to their original positions, he thought of using springs: one is a torsional spring and other is a linear spring. He attached the torsional spring (case 1) to the crank at crank hinge as shown in Fig. (19) and linear spring(Case 2) to the slider as shown in Fig. (20). He evaluated these two cases for State3. Since these satisfied, he evaluated for State2 and State1also, Since all were satisfied, he selected these as solutions till State3. Now he proceeded with the case1 arrangement (i.e. the arrangement in Fig. (19)) to evaluate for State4

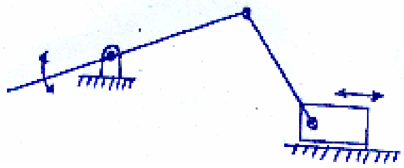


Figure 17: State1 solution synthesized by Designer 2.

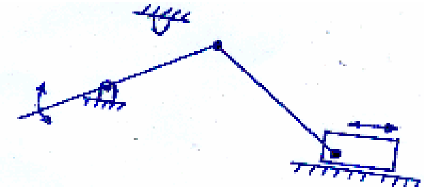


Figure 18: State2 solution synthesized by Designer 2.

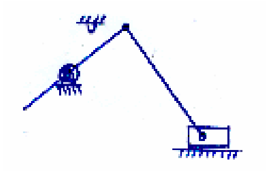


Figure 19: State3 solution by Designer 1.

and modified it by providing a slot in the slider to allow the revolute joint in it to slide in that slot. Now he evaluated for State4. As it satisfied he went further for State5, he modified the arrangement by proving a linear spring

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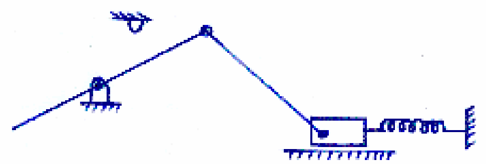

Figure 20: Linear spring arrangement to satisfy State3 requirement between the end slider and the frame. Now this satisfied all the five states. Next he went on to case2 (the arrangement in Fig. (20). As it satisfied for States3, State,2 and State1, he modified it for States4 and State5. He made a slot in the slider as shown in Fig. (21) and evaluated for State4 and later State5. As all are satisfied, he compared the two cases

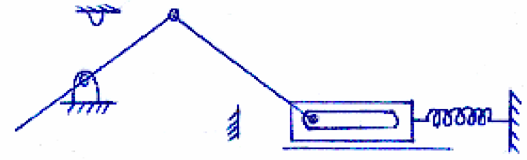

Figure 21: The solution which satisfies all the states.

and found that torsional spring in the arrangement of case1 is redundant. Now case1 and case2 are the same.

5.3 Observations from the above Three Synthesis Processes

If the above three synthesis processes are analyzed and compared, we can fit a common model for all the three synthesis processes as shown in Fig. (22). The need is converted into a set of functional requirements and these functional requirements are divided into states and state transitions. Once a state and state transition diagram is established, the synthesis process starts. From the state transition diagram, a state, which has a non- zero input effort, input motion and output motion, is selected initially, and solution proposals, which fully or partially satisfy the requirements of the state, are generated. One by one these

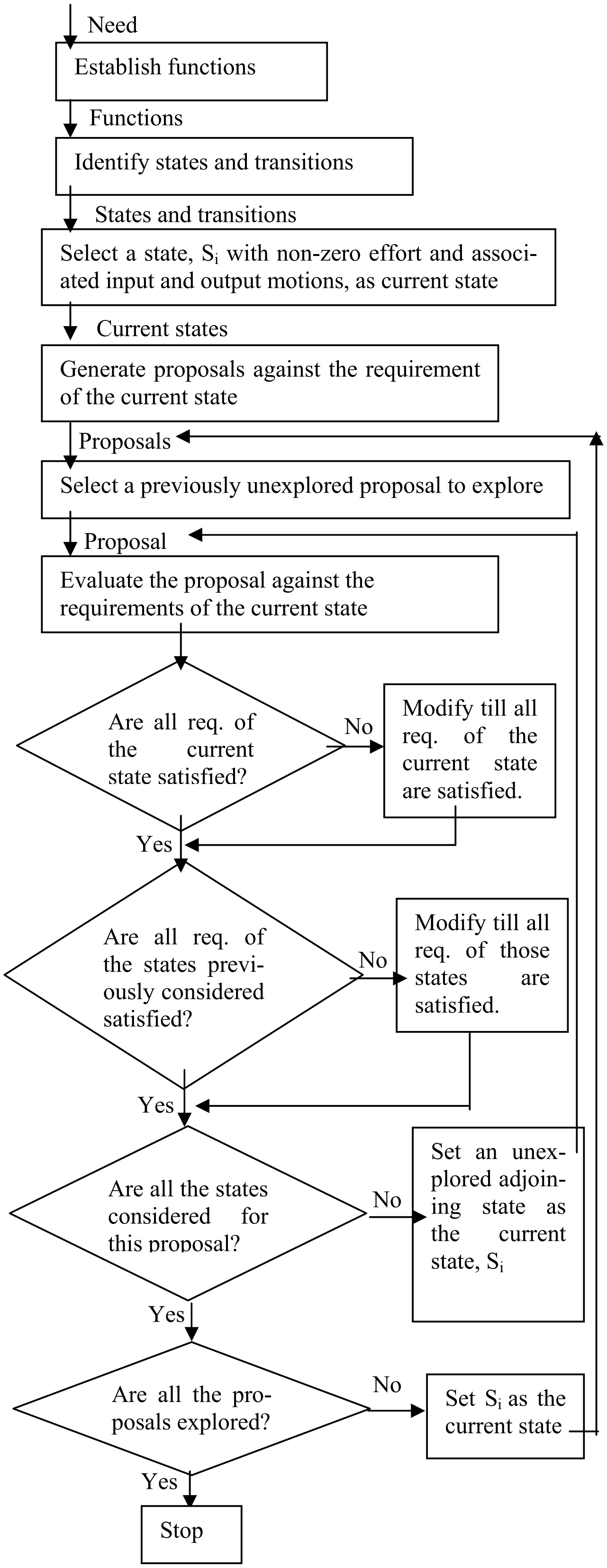

Figure 22. Common model for the synthesis process

solution proposals are taken for further exploration. A solution proposal is evaluated against the requirements of the state. If it doesn't satisfy any of the requirements of the state, then it will be modified to satisfy all the requirements of the state. The modification process happens as an iterative cyclic process till all the requirements are satisfied as shown in Fig. (23). The requirements of the state and the solution proposal which partly satisfy all the requirements are passed to a modification process, where a solution concept is generated to satisfy the unsatisfied requirements fully or partially and the solution concept is incorporated on the solution proposal and the modified solution proposal is again evaluated against the requirements. If it doesn't satisfy all the requirements, it will undergo the cyclic iteration process, till all the requirements are satisfied. If it satisfies all the requirements of the state, then it will be used for further exploration for satisfying other states taken one by one. If it doesn't satisfy other states, it will be modified till all the requirements of the other states are satisfied. So in this way, each solution proposal generated is evaluated and modified against the requirements of each state taken one by till to get a final set of solutions satisfying all the requirements of all the states.

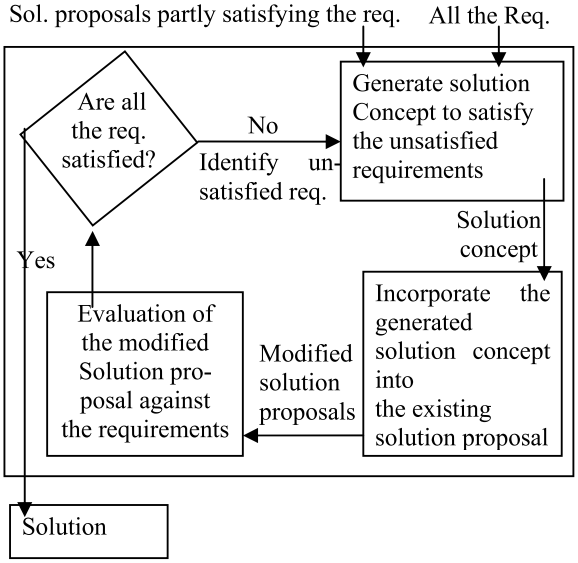

Figure. 23: Observed modification process

6 Automating the Synthesis Process of Multiple State Design Task

Note that none of the designers was able to individually generate all the variety of devices created by the other designers put together, even though they were asked to generate as many solutions as possible. This further testifies the need for a support that would help to develop all the solutions individually.

If the common model developed above is analyzed for possible automation, we identify a number of activities recurring through the process: representation of a device structure, function or behaviour and decomposition of these into elements to visualization of the device behaviour. There arise questions like:

- How could a computer visualize functions?
- How could it identify states from a set of functions?
- How could it visualize states and state transitions?
- How could it visualize elements, kinematic pairs or devices?
- How could it generate or retrieve solution proposals for any given state?
- How could it evaluate a solution proposal against the requirements of any given state?
- How could it modify solution proposals for unsatisfied requirements of any state?
- How could it evaluate or rank various device alternatives?

We need to understand which of these are possible to automate or support in order to enable a more complete search of the potential solution space for a design.

The process of multiple state syntheses of devices by designers will serve as the initial basis for piecing together a model of synthesis for devices of this kind. Knowledge underlying each activity will be hypothesized and used to develop support at various levels of automation. The proposed automated method will be tested on multiple state design tasks to verify its ability.

7 Conclusions

The concepts of mechanical device, state, single state and multiple state mechanical devices are established and in the context, the relevance of the present research work is explained. An empirical study of synthesis processes of three designers of a multiple state mechanical device is presented. A broad outline of the requirements for automated synthesis of mechanical devices is identified.

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