USE OF CONSTRAINTS IN THE EARLY STAGES OF DESIGN

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ABSTRACT

At the very early stages of original design work, the aspects of concept, scheming and analysis tend to merge. It is only as the designer's understanding of the design task increases that these aspects become more substantial and start to separate into distinct activities. The challenge in providing support in the early stages is that the design, and hence its geometry, is necessarily ill-defined. This paper looks at the use of constraint-based techniques as a design aid. Constraints are more clearly identified as they bound what is possible. They allow an initial model of the design to be created from the little that is known. This can be expanded as the design progresses, and, being constraint-based, previously created parts of the model can be refined in the light of subsequent design progress. These ideas are illustrated with an application based on the design of an "erection" system for cartons used for packaging. At the start of the design, all that is known is the form of the carton net. This is modelled to determine the required motion. The constraint model is then expanded to consider the basic folding mechanisms and the requirements for guiding faces.

Keywords: conceptual design, constraints, constraint-based design, packaging

1 INTRODUCTION

In order to try to understand the process of engineering design, a number of models have been proposed [1,2]. There are naturally differences between these models, partly in their levels of detail. There are however large similarities between the models. They all identify (under some name) four key stages: concept, scheming, analysis, and manufacture. These are shown in the simplified diagram given in Figure 1 [3].

In the *concept* stage, a potential design is proposed, possibly by the designer or by a client. This may simply be an idea (possibly ill-formed) with no indication of the geometry or details of what the eventual product will look like. In *scheming*, the basic form and dimensions of the product are obtained. Initially this is often in the form of rough sketches, and as the design task progresses these are developed into a complete specification and embodied to form a full engineering model (with engineering drawings as necessary). In order to ensure that the design will function correctly, some *analysis* needs to be undertaken. This could involve, for example, simulating the action of the proposed design or performing stress calculations to investigate its strength. Once the designer is satisfied that the design is workable, the product can proceed to the final stages of *manufacture* and test.

Naturally there are many feedback loops within the process. These are largely omitted in Figure 1. The one that is shown is perhaps the most significant. Three forms of design are often identified [1]: original, adaptive and variant. In the last two cases, the design lies within a class of products that already exist and with which the designer is already familiar. This means that information (in terms of geometry and layout) is currently available. Here the concept stage is the proposal an appropriate modification of an existing design and the next stage is largely analysis to ensure that the modified form is workable. Once this is the case, the scheming stage consists mainly of updating existing information for the modified product. This represents a clockwise movement around the loop linking the first three stages in Figure 1.

The design falls into the "original" category when the designer is unfamiliar with the application and what is required. Here the concept stage passes mainly to an initial scheming activity in which ideas are tried out. A little (elementary) analysis can take place while the designer gains an understanding of what is possible.

Often it is found that the design problem is over-ambitious and then the concept needs to be modified to allow feasible solutions to be available. Now the movement becomes anticlockwise around the loop shown. Once one or more potential design solutions have emerged, the analysis activity takes over to test whether these are workable and to try to identify which is best.

What is happening here is suggested by the diagram shown in Figure 2. At the start of an "original" design, the designer lacks understanding of what is possible and is at the centre of the spiral. The activities of concept, scheming and analysis merge within the mind of the designer as ideas are considered and their worth assessed. As the ideas become more concrete, there is movement outwards around the spiral: there becomes more geometric information available and hence more that can be assessed. The activities of concept, scheming and analysis start to be more separated. This is partly because they become more time consuming. As this happens, nature of the design space is being explored. The designer's understanding and confidence increase, and there is a better awareness of what can and cannot be achieved. As part of this, the requirements, the design, and what needs to be analyzed become more well defined.

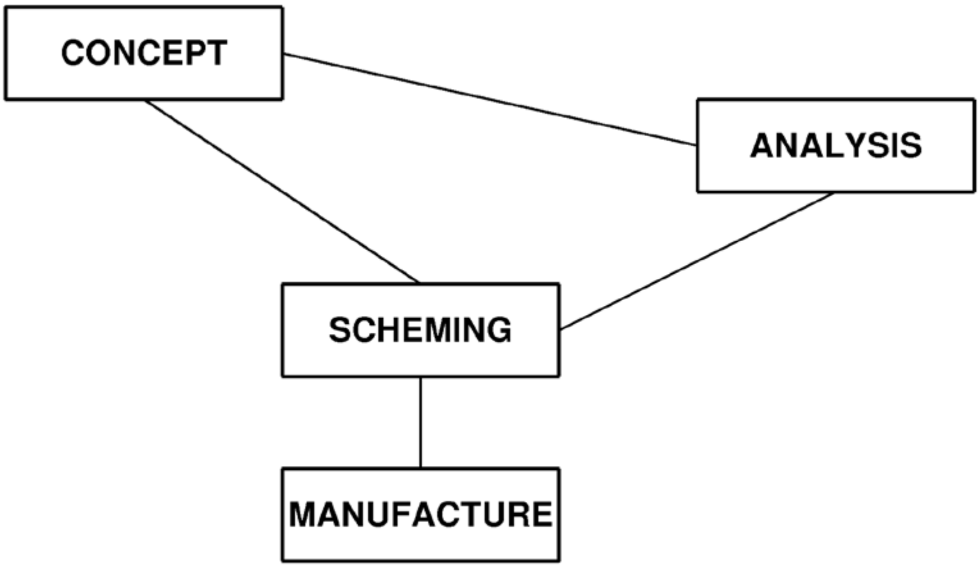

Figure 1. Main activities of the overall design process

It is not always necessary to undertake analysis by sophisticated means (such as, say, the use of a finite element package). As an example, consider the situation of obtaining a mechanism to achieve a prescribed motion within a given space. If a proposed mechanism is much larger than the space available then it is clearly invalid. Conversely, if it turns out that the mechanism is much smaller than the space, there is no need to undertake extensive checks for clashing with the environment. But if it is of comparable size, then such a check is of course vital. (This may require some form of specialized analysis package, but this is usually employed somewhat later in the design process.) In this way, as the design task becomes clearer, so the requirements for analysis, and the necessary tools, also become better defined.

Some steps towards support for the early stages of design are available. In machine design for example, there are methods for finding mechanisms to create given paths or functions [4], and approaches to support type synthesis [5]. In the cases of adaptive or variant design, the form of the design solution is known and parametric means can be used to undertake some of the subsequent design stages [6]. More generally, there has been some interest in methods for generating ideas at the early conceptual stages. One possibility is to take inspiration from nature [7,8].

While these techniques are important, many of them make certain assumptions about the nature of what is being designed. They are thus most applicable on the outer parts of the spiral (Figure 2) when the designer's understanding has reached a certain level and the design problem has become well-defined. While they are vital in ensuring that a design is satisfactory, they may not provide much assistance in the early parts of the design process. It is certainly difficult to provide the designer with help here, if only because there is little or no geometry to deal with. What is available instead are ideas which are more abstract and hence more difficult to deal with. This includes information about the form [9] or function [10] of the design.

At the early (conceptual) stages of any design, progress is not always “logical”; it is partly based on trial and error. This is because of a lack of understanding and the absence of well defined criteria [11]. However, what can help the designer is the ability to explore the design space. This can help to increase understanding and give additional insight into the design task. Indeed it is this ability of the human designer to assimilate the results of such exploration that is a positive advantage and needs to be exploited [12]. Some exploration can be carried out using conventional CAD or other graphics systems. However the structure of such systems, while highly suitable for the later stages of design, create barriers in the early stages [13].

This paper is interested in the use of a constraint-based approach in the early stages of conceptual design and the related activities of the scheming and analysis: this is the inner part of the spiral. Constraints have been used for some time to handle geometrical issues within CAD systems [14]. They have also been used represent knowledge and ideas within the design process [15]. Constraints are somewhat easier to identify in the early design stages as they capture known limits: more positive information only becomes available as the design problem begins to be understood more fully.

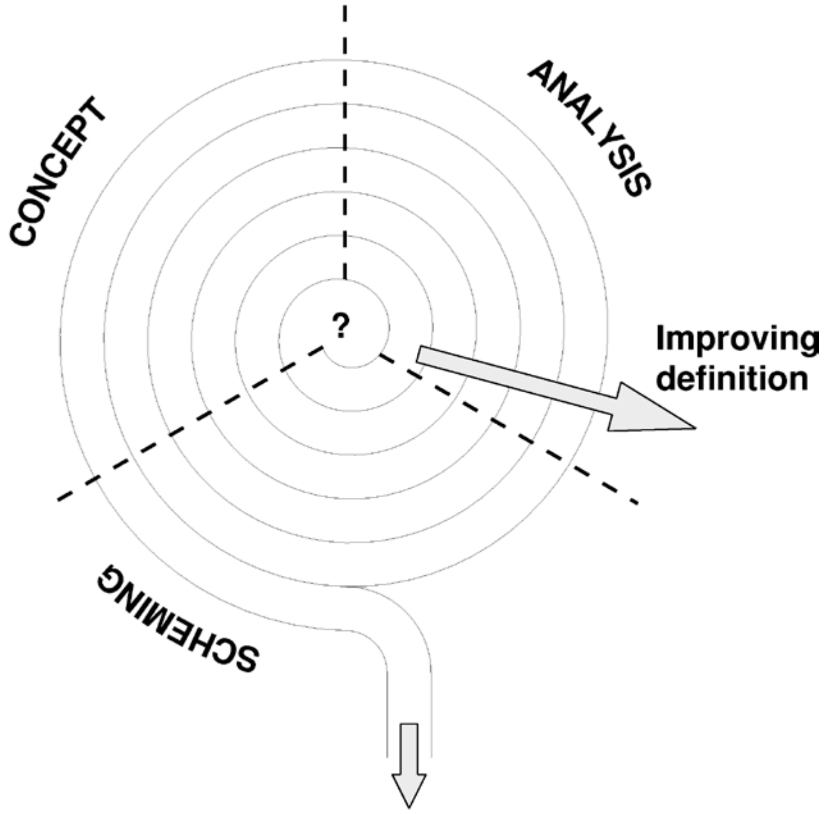

Figure 2. Spiral of confidence: from ill-understood to well-defined

A constraint-based software environment is used here and it is shown how this can be applied at the early stages of a design application. The environment aims to give the user insight into a design task and to allow the model created of the design to be expanded as understanding grows. It enables the user to identify potential problems and hence to be able to formulate these in a well defined way (moving outwards around the spiral). It helps the user to check which are the critical aspects of the design.

In this way, it aims to allow the designer to explore some of the design issues and so gain additional insight. The environment does not aim to solve (in any rigorous detail) those problems which it helps identify. That is something which relies upon the problem-solving skills of the designer, alongside the use of specialized computer procedures. But the environment does provide help in exploring potential alternative solutions.

The approach is discussed by way of an application to the design of an item of packaging equipment. Cartons for packaging (for food products, for example) are normally supplied as flat nets. They need to be “erected” into their final shape. This can be done manually or, preferably, by mechanical means [16]. A designer of packaging machinery is often presented with a new carton style and is required to find a means for automatically erecting it. Trying to establish the basic form is a case of working at the conceptual stage of the design process. This requires ideas to be identified for discussion with the client and for possibilities to be explored and refined [17]. Catalogues of mechanism types (and their outputs) may well come into play [18,19]. However, a full mathematical or computer model cannot be obtained until the design has been sufficiently progressed.

What is helpful is a design procedure whereby the designer to capture that information which is available, albeit sparse. This information certainly includes the geometry of the carton net. This means that there is enough information to allow the design procedure to simulate the erection process in terms of the carton alone. The approach adopted forms an example of the use of geometric constraints [14]. The basic carton net can be described in terms of the positions of faces and the transforms which relate them. When loops of faces exist, some of the faces involved move as a result of others being explicitly driven. Constraints can be applied to model this situation and to determine the angles of the following faces. This is discussed in section 2.

The simulation can then be used to investigate alternative erection strategies in terms of the mechanisms and other equipment involved, and hence select and optimize the most suitable design. Here the constraint-based model is expanded to include and explore the erection system and constraints now involved relate to other requirements beyond the purely geometric. The extended model is used to ensure that the erection process works as expected (at high speed) and, in particular, that there is no unwanted interference between parts of the net as it is folded. Such a model could be achieved by setting up explicit equations and then solving these. However this offers little flexibility. What is more useful is some form of visual simulation (as used for example in [20,21]) and the ability to investigate the effects of modifying the imposed constraints. The creation of the expanded model is given in section 3.

The system used to resolve constraints is based on optimization. This means that a designer can consider trying to improve performance parameters. It also means that constraints can be resolved even when conflict exists; this yields a compromise configuration. This is exploited in section 4 when mechanisms are investigated to guide the non-driven faces in the carton study. Here useful design information is successfully obtained by applying constraints which can be satisfied fully only for part of the erection process.

2 USE OF CONSTRAINTS

It is proposed that constraints are useful in the early parts of (conceptual) design. This is because the designer needs to explore design possibilities and full information about the geometry involved has yet to evolve. What are clearer are the constraints which bound what is possible. This idea is illustrated with the use of a case study from the design of packaging machines, specifically equipment to “erect” a carton tray. Cartons are normally supplied to a packaging company as “blanks” which are initially flat. They have the appropriate cut shape, and the required creases have been scored but not fully formed [16]. The blanks need to be “erected” (that is folded) into the three dimensional shape. During erection, folding around the pre-defined creases is imposed.

Figure 3 shows an example of a carton net which folds to form a standard rectangular tray. Its face graph, shown in Figure 4, has a node representing to each face (panel) of the net, with two nodes being connected if the corresponding faces are adjacent. The graph contains loops. This means that the creases cannot be folded independently and the motion of the faces during erection needs to be carefully controlled. The folding is usually carried out by a collection of mechanisms working together within a packaging machine.

A simulation of the erection can be obtained with a computer model which shows each face. Figure 5 shows stages in such a simulation. Rotations are applied to some of the faces so that each is driven and turns about the crease joining it to its neighbour. As the rotations are not independent, the rotations of other faces need to be determined as a result of the constraints imposed by their neighbours.

In the example shown, such dependent faces appear in the corners, for example, the faces numbered 2 and 3. The positions of faces 1 and 4, together with the fact that faces 2 and 3 are joined, imposes a constraint on the positions of these latter two faces. If the faces are regarded as being split along the line of their common crease, then the constraint is that their corners P and Q (shown in the figure) must coincide.

Several approaches to geometric constraint solving have been investigated (e.g. [14]). The one used here is a constraint modelling environment [22] which allows manipulation of wire-frame entities including points, lines and (shaded) faces. The user interface language allows such entities to be defined and constraints imposed between them. In the case of faces 2 and 3 in the above example, the constraint to keep them together is given by the following command.

```
rule( P on Q );
```

Here `on` is an in-built function which determines the distance between two geometric objects, in this case points *P* and *Q*. The convention is that a constraint is an expression which is zero when it is true; any other value is a measure of its falseness.

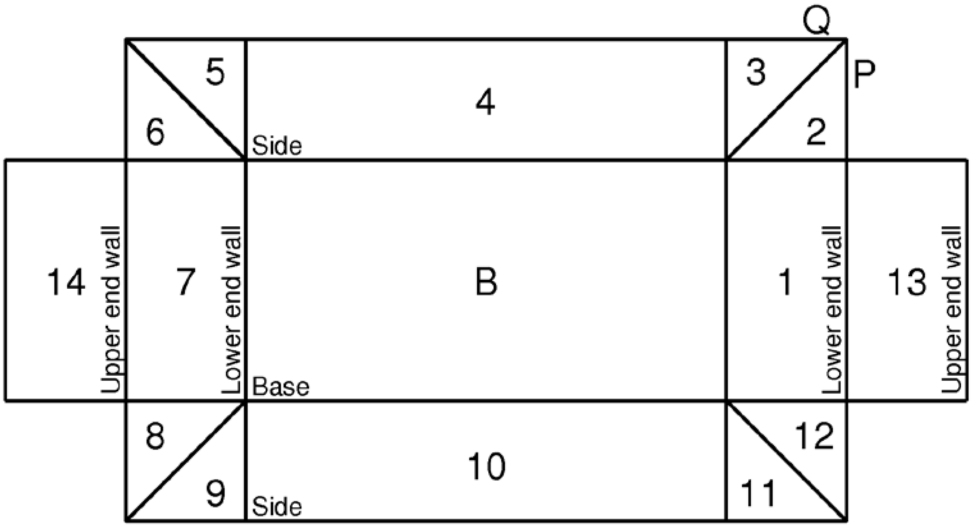

Figure 3. Net of tray carton

Optimization techniques are applied to resolve constraints and this has the advantage of allowing progress to be made even in cases when the imposed constraints are in conflict. When several constraints are imposed, the environment forms the sum of the squares of the constraint values and looks to minimize this. Naturally the form of the imposed constraints is not known in advance and so direct search optimization techniques are usually used. (It is Powell's direct search method that is used for the examples given in this paper.)

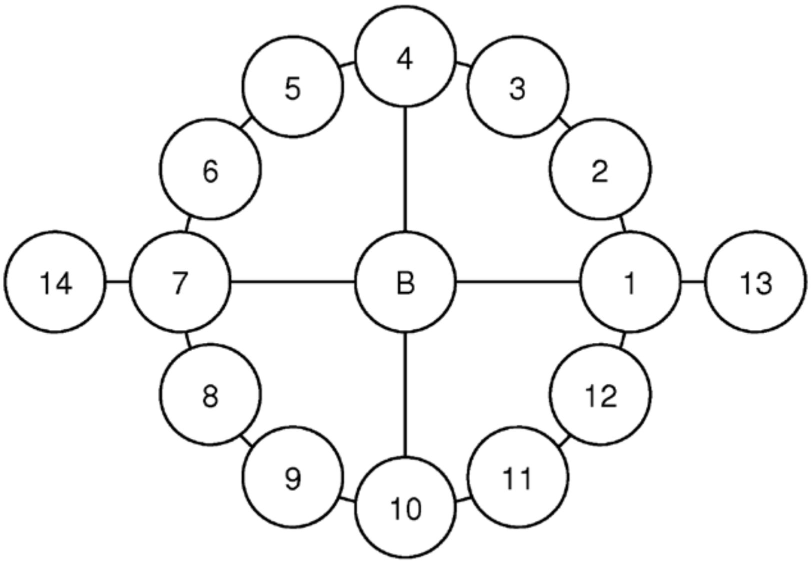

Figure 4. Face graph of tray carton

There are two advantages to the use of optimization techniques for resolving constraints. Firstly the system can work even if the constraints are in conflict. What is obtained is some form of "best compromise”, with the imposed constraints taking on minimal falseness values. This is particularly advantageous in the early design stages when understanding is still limited. Secondly, it permits possible design improvements to be investigated. For example, a performance measure can be specified as part of a constraint. The system can then be used to modify design parameters to try to improve this measure.

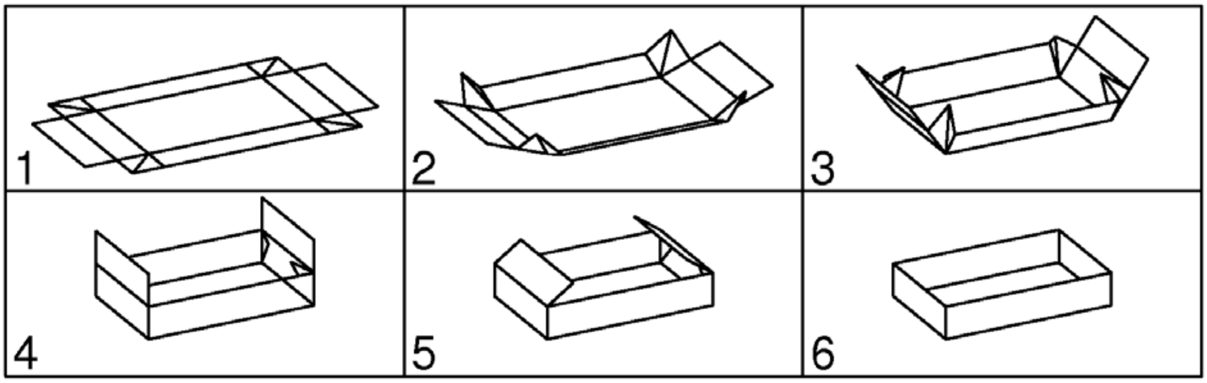

Figure 5. Six stages in simulation of erection of tray carton

3 MECHANISM DESIGN

As a design progresses, it is useful to expand the design model to investigate further possibilities. The use of a constraint-based approach means that this can be undertaken without the need to fully define all the design parameters. Instead, these can be introduced as the designer’s understanding increases. Here the applied constraints start to move away from the purely geometric.

In the case of the carton erection example, the initial model establishes motion of the carton itself. The model now allows the motion requirements of the equipment to perform the erection to be defined. In particular, the number of degrees of freedom can be identified. This allows a search for potential design solutions to start.

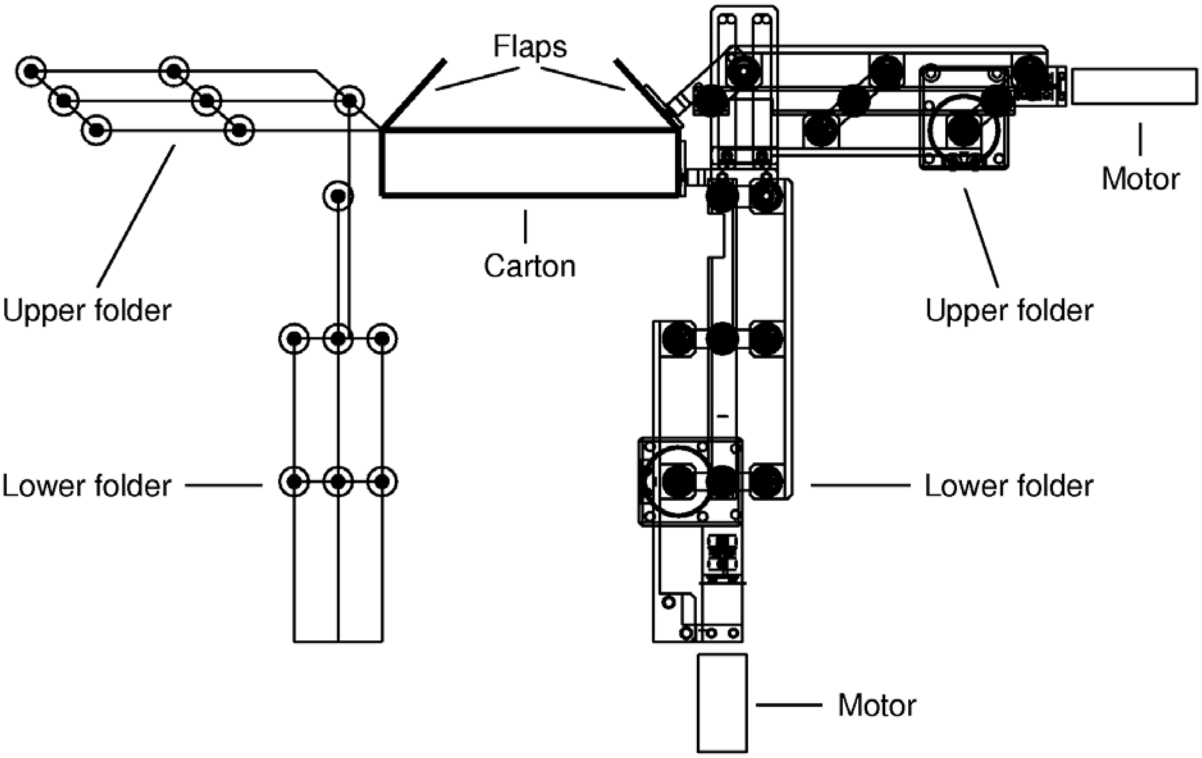

Figure 6. Carton with double-folder mechanism: left - stick model; right - embodied model

An appropriate design solution commonly takes the form of a mechanism such as a four bar linkage. This can be investigated within the constraint-based environment, building the model of the mechanism system as an extension to that for the carton itself. This means that constraints can be introduced to maintain contact between the erection mechanism and the appropriate faces of the carton. Constraints are additionally imposed to indicate how the individual links of the mechanisms assemble and interrelate. Effectively, the motion of the erection system is derived by driving it from the required motion of the carton. In cases where some degree of reconfigurability is needed, so that a range of similar cartons can be handled [23,24], the expanded model can be used to ensure that a chosen design has the capability to cope successfully with the entire range.

Data about the cycle time required for each carton can also be generated. If a potential mechanism is already available, the simulation can be used to determine the optimal position and orientation in which to set it up for a given carton size.

Often the representation for an erection mechanism begins as a simple “stick model” in which the links are represented simply by line segments and the joints by points. This may be expanded with the introduction of more lines representing additional links used to control the motion. For example, Figure 6 shows the tray carton in a partially erected form. On the left is the stick model of a double-folder mechanism which consists of two single-folders: one to turn the inner part of the end flap into the vertical position; the other to turn the outer part over and inside the tray.

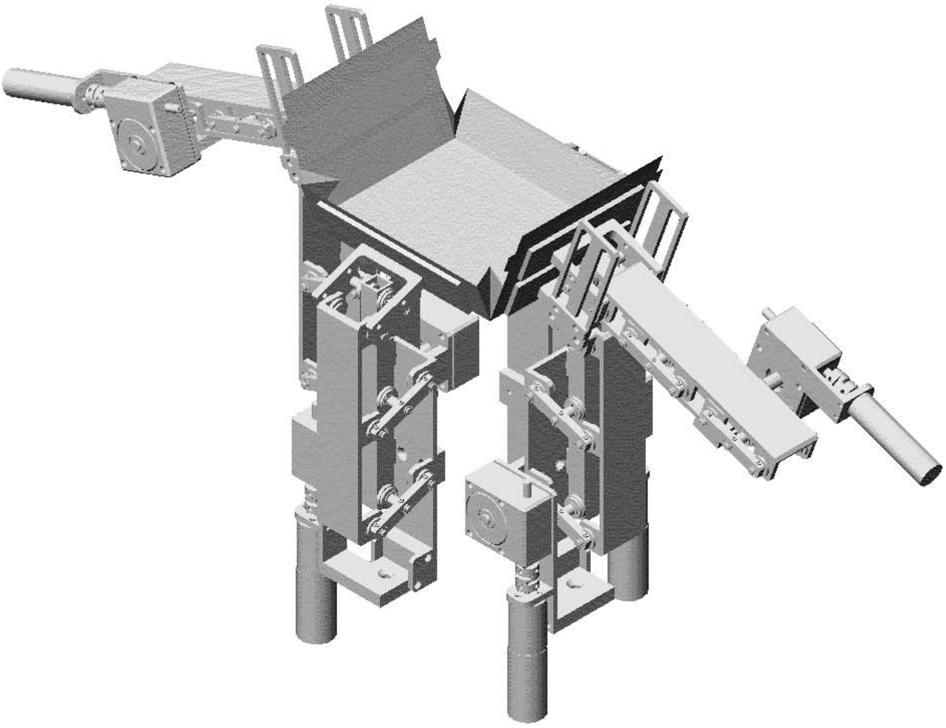

Figure 7. Four folder mechanisms erecting tray carton

The sets of three parallel lines represent links which remain parallel throughout each of these folding operations and enable turning to take place about a virtual axis coincident with the crease in the carton. On the right of the figure, the same mechanism is shown but with significant further development including the addition of embodiment for the links and the motors to drive the motions. Figure 7 shows a surface representation with folder units (two double and two single) around all four sides of the tray. Here the model has been further enhanced and can now be used to check visually that the motion is as required and that no problems arise due to clashing between parts.

4 GUIDES

As a design progresses, more and more parts of it are investigated and defined. However, it may become necessary to modify some previously established elements in order to allow some of the subsequent aspects to operate correctly. This is illustrated with the carton example by considering the guides mechanisms needed to ensure that the “gusset” faces in the corners of the tray move correctly. There is some choice about the path along which these travel. It is preferable for the final stages of the erection that they lie close to the main end walls of the tray. The constraint-based approach allows this to be investigated and the operation of the existing design is maintained even though the assumption (previously made) that the gussets move "symmetrically" no longer applies.

Up till now, the constraint-based environment has been used to investigate the motion of the carton and to identify and embody a mechanical means for folding the main side faces of the carton. As noted before, the positions of the gussets faces are determined by the motion of the main sides. However, the gusset can potentially move either upwards (correctly) or downwards. To ensure the correct motion, some form of guide is required to encourage upward motion. Additionally there is a question about the path the gusset faces should take. As Figure 7 shows, all the side faces can be driven at the same constant speeds so that the gussets move symmetrically between the sides.

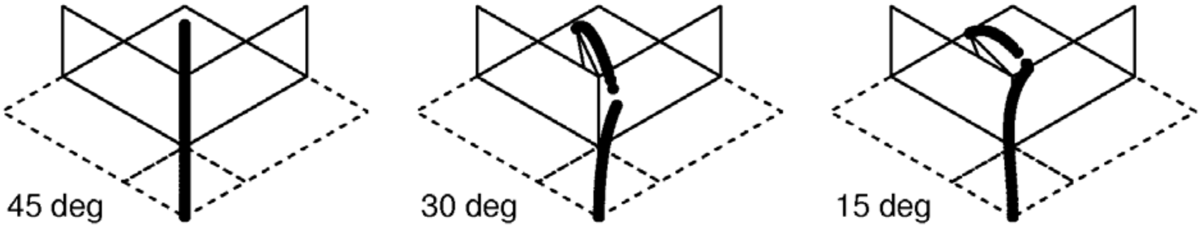

Figure 8. Track of top corner of gusset for different angles relative to the end wall

The final stage in the erection is to turn the upper faces of the ends over and into the tray. This process captures the gussets and forces them against the end walls. In practice this is successful for many cartons. But there exists the possibility of trying to arrange that the gussets lie closer to the end walls so that they can be captured more surely by the upper faces. This requires the side faces to be moved at different rates.

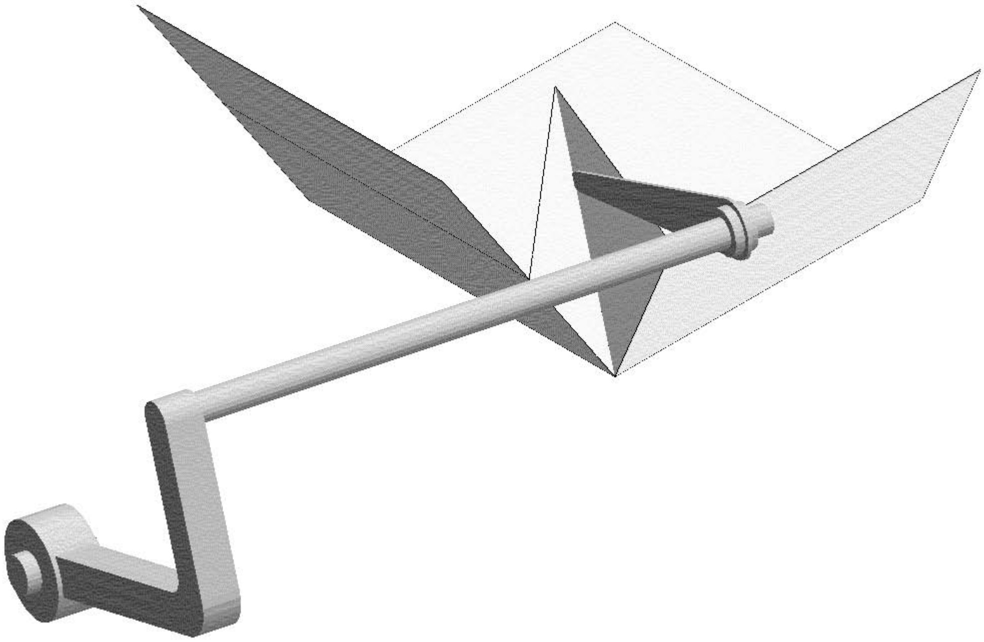

Figure 9. Model expanded to include a blade guide acting at a corner

The initial model of the carton erection is driven on the basis that the faces have equal rotations. It is a simple matter to revise the model (retaining the existing constraints for assembly) to impose a constraint that the tip of the gusset should lie on a line at a particular angle to the end walls. Then just two of the side faces are driven and this additional constraint enables the angles for the other two sides to be determined. At the start of the motion, the additional constraint cannot be satisfied: it conflicts with the constraints of the geometry. However the constraint-based approach still works successfully since a compromise solution is achieved. Once enough rotation has been achieved, all the constraints can be satisfied together. Figure 8 gives the resultant motion of the tip of the gusset when the angle with the end wall is 45 degrees (the original symmetric case) and when it is reduced to 30 and 15 degrees. In the latter cases, the tip only reaches and moves along the desired line towards the end of the motion.

In order to achieve the required guidance, a mechanism which is essentially a thin rotating blade is considered. This rotates about an axis through the appropriate lowest point of a corner as suggested in Figure 9, which just shows the region around the corner. This can be added to the model and a constraint imposed to make the tip of the blade lie on one of the gusset faces and, in particular, on the central crease.

Again the latter additional constraint cannot be achieved (exactly) in the early stages of the motion but the environment still provides compromise results which are nonetheless usable. In this way, the enhanced model is able to give sufficient information for the designer to assess whether the idea is worth pursuing and what angle (or angles) with respect to the end wall need to be further considered.

With the angle selected, the constraint model can be used to determine the angular positions of the folder mechanisms and of the guide blades. These values can then be taken as input to the motor controller used to run the physical mechanisms.

5 CONCLUSIONS

In the early stages of design, particularly for “original” design, the designer naturally experiences a lack of understanding and confidence. The aspects of concept, scheming and analysis coalesce in the mind of the designer as ideas are examined and potentially suitable ones are identified. As the design progresses, these aspects become increasingly separate. It is difficult to provide aids for the early design stage, partly because the conventional approaches to computer aided design rely heavily upon the modelling of geometry.

What are more apparent in the early design stages are the constraints which bound what can be done. Constraints can also help express more abstract concepts such as form and function. This means that a constraint-based approach is one way to support initial design work. During design exploration, the inherent lack of understanding means that those constraints which can be identified are likely to be in conflict. This does not matter provided the means used to resolve constraints can take account of such conflict. Indeed, it is partly by imposing inappropriate constraints and seeing their effects that the designer gains a greater appreciation of the design task.

The creation of an initially simple constraint-based model allows the design space to be explored and one or more potential design solutions to be generated. The model can then be expanded to add more detail of the design. The constraint-based nature means that it is straightforward to modify previous design ideas to take account of the results of subsequent design work.

These ideas have been illustrated in relation to the design of mechanisms to “erect” a packaging carton from a flat blank. The initial model is based around the blank itself and the motion it needs to perform during erection. This is then expanded to include a simple representation of the erection mechanisms with constraints to specify how these mechanisms assemble and how they relate to the carton. The model is further expanded to include the embodiment of these mechanisms. Additional features can be added, in this case guide mechanisms, and their action implemented and investigated by imposing alternative constraints on the motion of previously defined elements.

In this way, the constraint-based model allows a design task to be explored, thus providing an understanding of what is possible. The model expands and evolves as the design process progresses and the designer’s understanding increases.

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