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USE OF PARAMETRIC MODELLING TO UNDERSTAND THE FUNCTIONAL REQUIREMENTS FOR A RECONFIGURABLE PACKAGING SYSTEM

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ABSTRACT
In the area of packaging, the use of cartons is an important one. The style of the carton is governed by a number of factors. There is often a need to wrap distinctive seasonable or other market-driven products and to do so for batches of small size. There is attraction in using reconfigurable systems in such cases. As part of the design of such systems it is important to be able to model and simulate the carton formation process to understand the process and to ensure that it behaves as expected. What has been found is that such models allow the common motions required of packaging systems to be identified and that this provided initial design information for the design of new actuation systems and the optimal positioning of existing ones.

Keywords: Packaging, Reconfigurability, Design iteration, Constraints

1 INTRODUCTION
In the packaging industry, constantly changing market demands put pressure on food manufacturers to use innovative packaging designs. However, there is a lack of flexible packaging machinery [1]. This means that new carton designs for seasonal products, which cannot be produced on conventional dedicated machinery, are erected manually [2]. The desire to reduce waste resulting from manual erection [3], recruitment difficulties associated with seasonal labour, moves towards mass customisation [4] and the need to facilitate integrated design of product and packaging [5] all contribute to a high demand for a flexible packaging system using reconfigurable techniques.
A recent project has been undertaken in the area of reconfigurability, dealing principally with the area of carton forming. At the start of this project, there was insufficient understanding about the functional requirements of such a reconfigurable system for design solutions to emerge. In particular, the motions needed to form a range of cartons were undefined, as well as issues such as production speed in comparison to existing dedicated machinery and cost implications.
This paper discusses the use of modelling tools to analyse information about a range of cartons and systems to form them, establishing an evolving understanding of the problem. This started with the creation of a parametric carton model, allowing a range of cartons to be considered. Analysis of the forming motions of these cartons within the model led to the determination of a set of generic motions that could be combined to form the whole range of cartons. The model was then utilised as a support tool [6], during iterative evaluation and refinement of the design solution (in this case a new mechanism system). It could also be used to evaluate the use of pre-existing mechanisms in terms of their cycle time for different cartons, and optimal positioning.

2 DESCRIPTION OF THE MODELLING APPROACH
This section describes the software environment used for the modelling activity. This happens to be a parametric modeller that allows constraints to be introduced between design parameters [7,8]. Other forms of parametric modeller can also be used.
In this constraint modelling environment, it is possible to group geometric entities together within a "model space". Effectively the entities are defined in the own local coordinate system and a transform associated with the space indicates how they map into the world coordinate system. Alternatively, the

transform may indicate how they map into the coordinate system of another model space. In this way a hierarchy of spaces is created. Loops are not allowed within the hierarchy as these would potentially cause conflict in the definitions of the transforms. Instead the hierarchy is a tree and the "root" of the tree is the world space. To find how the entities within a given model space map into world space, they need to be mapped by the combination of all the transforms between the local space and the world.
This form of hierarchy is often used to obtain an initial assembly of a collection of parts, which could for example be the links of a mechanical system [9]. Additional relationships between the parts are normally required to determine the full assembly. Care is required in dealing with the transforms because of the possibility of conflicting requirements. In the constraint modelling environment, this is achieved by specifying constraints between geometric entities. These are commonly that two (or more) geometric entities must be coincident or, at least, in some geometric relationship. The system then adjusts the variable parameters in the applied transforms to try to reach a configuration in which the constraints become true. The established hierarchy of model spaces ensures that the initial assembly still remains valid after such adjustment.

3 DESCRIPTION OF CARTON MODEL

The first iterative stage of the design process involved the gathering together of as many examples of confectionary cartons as possible. A selection of the case study cartons is shown in Figure 1.

Figure 1. Selection of case study cartons

In the parametric model of a carton, each panel can be represented initially in wire-frame form as a series of boundary lines. Those for each panel are set in an individual model space, which allows them to be moved together as a group. There are relations of adjacency between the panels which can be represented as a tree diagram [10] and this relates directly to the similar hierarchical structure of the model spaces. Examination of the case study cartons showed that they were either folded directly from a flat mesh, here referred to as the origami approach, or they are erected from a pre-folded and glued sleeve, here termed the skillet approach. The hierarchies for the panel relationships for these two types are shown in Figures 2 and 3. For the origami approach, the "root" node of the tree structure is the base of the carton, with the side panels all arranged adjacent to this. For the skillet approach, the root node is one of the side panels (which is typically held by vacuum during forming). The side panels are arranged in series relative to the root node. The pre-gluing is represented by the dotted edge in Figure 3; this means that a constraint is required to specify this feature. All other features of the carton were found to be arranged relative to the side panels irrespective of the carton type.

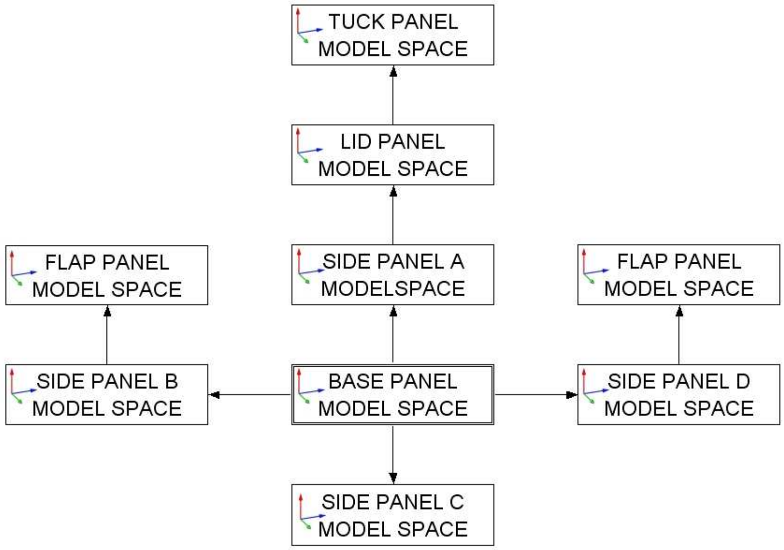

Figure 2. Model space arrangement in the origami model

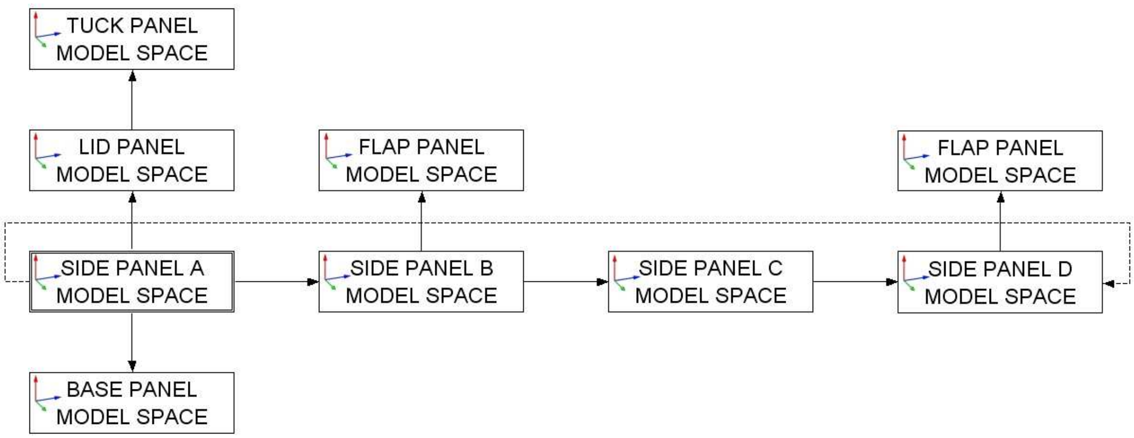

Figure 3. Model space arrangement in the skillet model

Within the model the carton could be manipulated by translating and rotating individual panel model spaces. Constraint rules were used to vary the degrees of freedom of all other model spaces to ensure that assembly conditions were met in order to maintain the panel interrelationships during manipulation. Through the process of unfolding an assembled model the preferred order of folding was determined.

This approach enabled basic, rectangular cartons to be modelled. However, a greater understanding of carton geometry was needed in order to construct more complicated features such as tapered side panels, "gable" style tops and "corner gussets", necessary to reproduce the range of cartons shown in Figure 1. Information about these geometries was generated through measuring the case study cartons, and then analysed by replicating them using constrained sketches within a commercial CAD system. This enabled the geometric form to be explored and the effect of variables such as side angles, widths and heights of gussets on the geometry to be investigated. Two examples of the resulting carton nets are shown in Figure 4: one has an example of corner gussets, the other has a gable top.

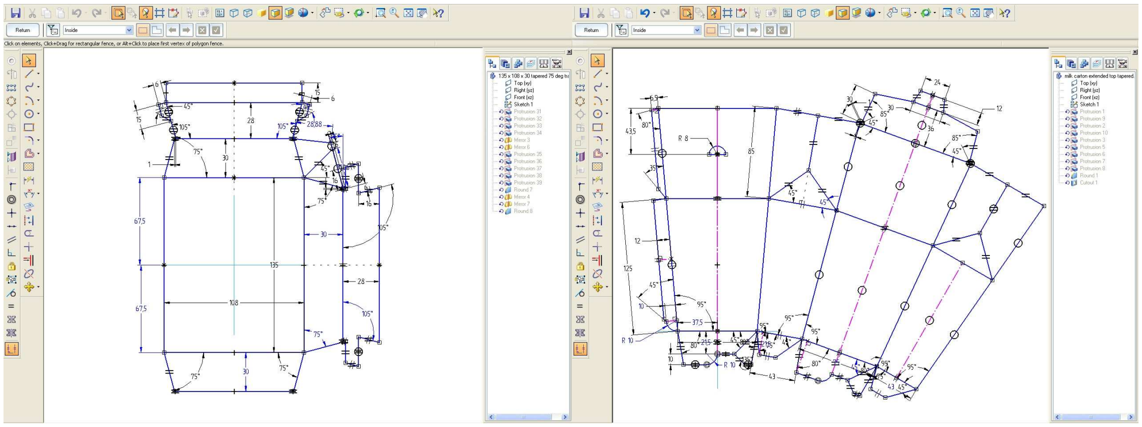

Figure 4. Constrained parametric nets created within a commercial CAD system showing corner gussets (left) and gable top (right)

With the tapered cartons shown in Figure 4, it is important that the relationships between dependent variables are found, in order to avoid distortion of the carton panels during folding. The nets were validated by printing them onto cardboard and then manually erecting the cardboard cartons. A selection of these is shown in Figure 5.

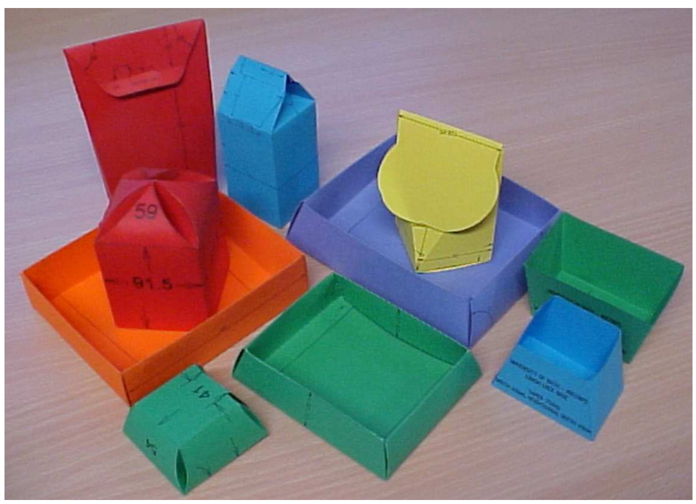

Figure 5. Cardboard cartons used to validate the geometry

The meshes created for these were then transferred into the constraint modelling environment. The resulting layout of panels and fold lines was initially in a flattened form. The model spaces within the hierarchy were translated and rotated relative to each other such that only one rotational degree of freedom was needed per model space in order to maintain the assembly of the carton. As with the basic model, the carton forming was simulated by manipulating the rotation of one panel's model space, and using constraint rules to rotate all of the other model spaces until the assembly constraints were met.

The use of separate functions within the underlying language of the environment allowed the creation of various types of panel and enabled them to be combined in different ways to create a variety of carton forms. For example, the variable controlling the number of side panels in the gable top carton (shown on the right in Figure 4) can be changed from four to six. This results in the carton net for a six sided carton as shown on the left in Figure 6. Similarly, a three sided carton based on one shown in Figure 1 can also be produced and is seen on the right in Figure 6. In order to investigate the scope of the approach in handling a complex range of products, a wide range of potential carton types were tackled. Each was generated, modelled and its formation simulated.

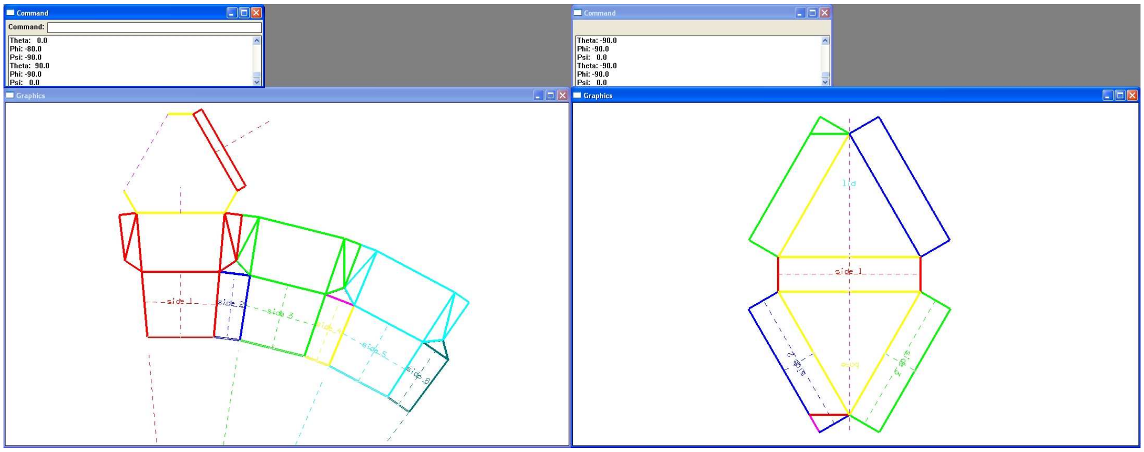

Figure 6. Generic carton simulation showing carton net for six sided gable top skillet (left) and triangular carton (right)

4 IDENTIFICATION OF COMMON MOTIONS

In this section, the analysis of the effect of motions on two carton models is described. A set of generic motions, identified after similar analysis over a wider range of cartons, is then introduced. Figure 4 shows the carton net for an origami tray carton (left), based upon a common style of packaging. The same model is shown in Figure 7, at various stages of the folding process, this time with shaded panels to aid visualization.

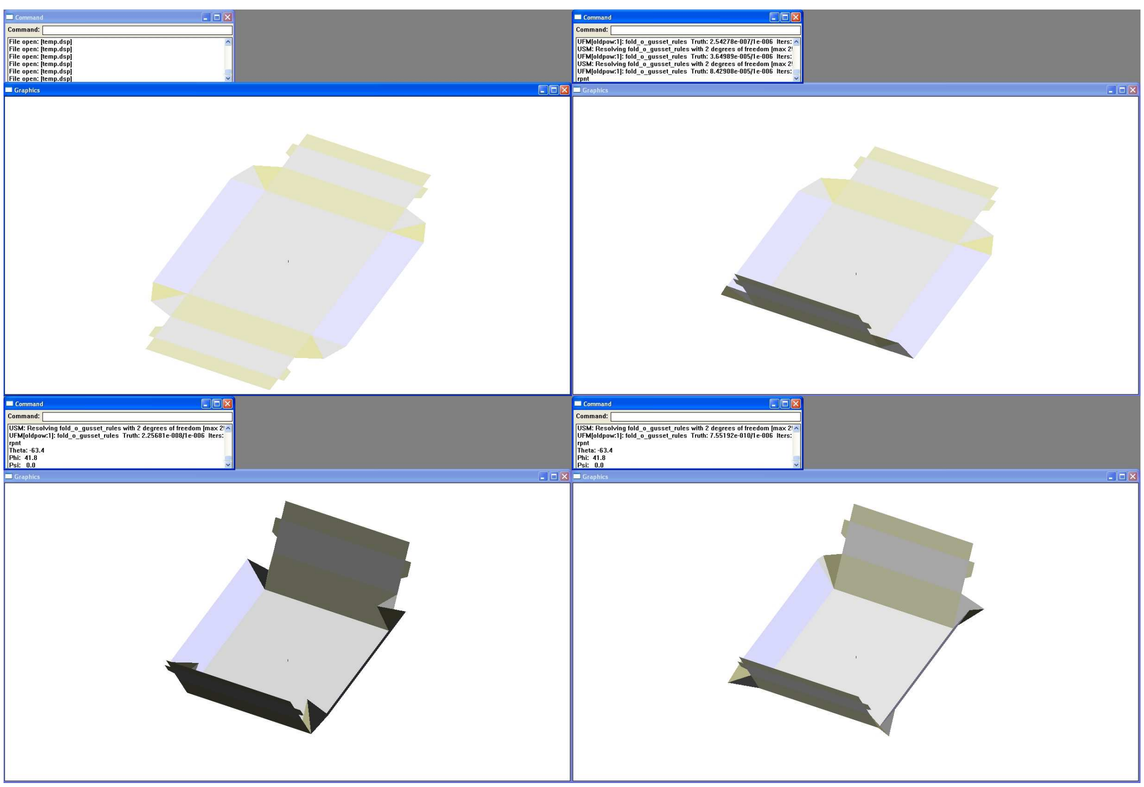

Figure 7. Origami tray shown flat (top left), with folds resulting from a single ground line rotation (top right), four simultaneous ground folds with gussets forced inwards (bottom left) and outwards (bottom right).

At the start of the folding process, the net is entirely in a flat plane, as shown in Figure 7 (top left). This plane is referred to here as the "ground". It can be seen from the top right of Figure 7 that folding a single side panel up from the ground (referred to here as a "grounded fold"), whilst simultaneously applying assembly constraints, has no effect on the position of the other side panels. Therefore, four grounded folds are required to form this carton, one for each side panel. The constraint rules applied to the corner gussets force them to follow the side panels. However, there are two solutions to these constraints, with the gussets either facing inwards as desired (shown in Figure 7, bottom left), or outwards (bottom right). There is therefore a need to incorporate a means of "guiding" the gusset motion during erection to encourage them to take on the required configuration.

Another common carton form is the gable-topped skillet carton and this was also modelled and studied. Here the carton blank is originally folded and glued to form a sleeve section. This is then flattened, by a "parallelograming" action, for ease of storage and transportation to the packer's site. The "as provided" skillet format is shown in the top left of Figure 8. In this case, the simulation shows that with the application of a single grounded fold to one side panel, the constraints applied to the other side panels force them to follow the motion, as shown in Figure 8, top right. These constraints correspond to the dotted line in Figure 3. To create the gable top, the side gussets again follow the main driven panels. There are again two possible solutions to the constraint rules, with the gussets either pointing inwards as desired (bottom left of Figure 9), or outwards (bottom right). There is therefore a need for a guiding motion to achieve the correct panel configuration.

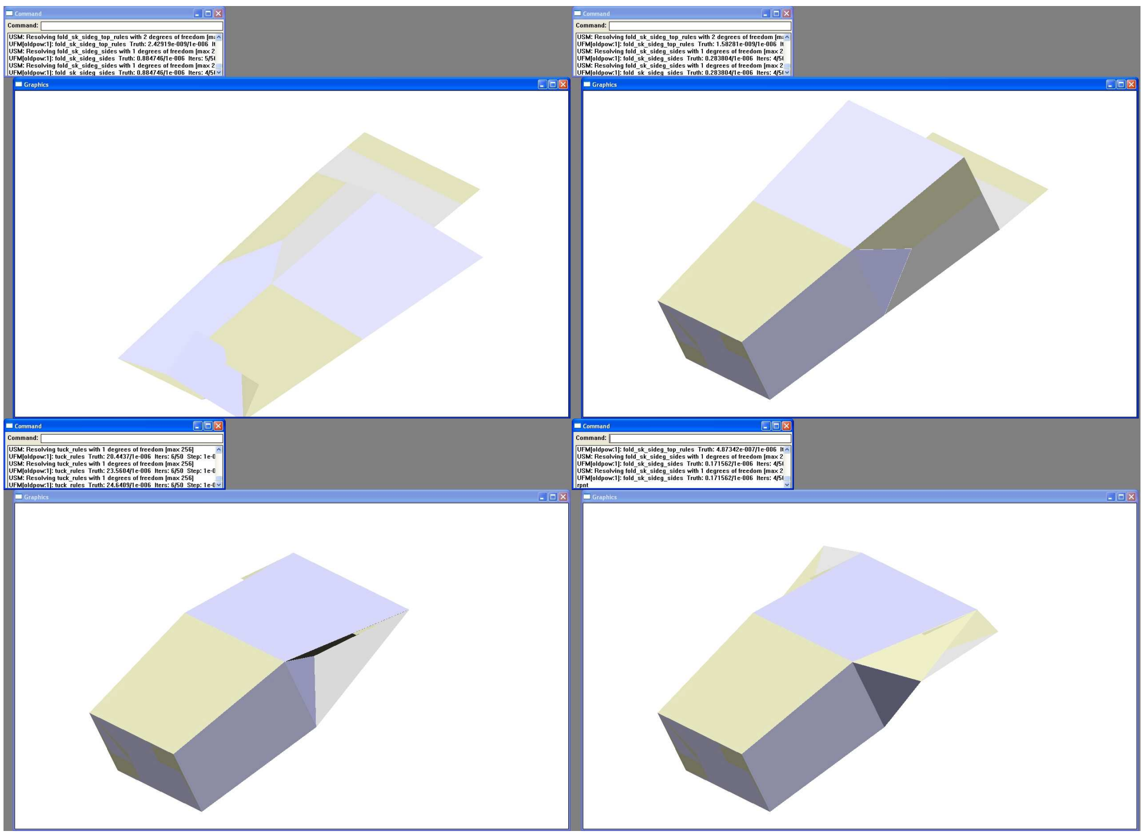

Figure 8. Showing a gable topped skillet carton showing similar erection processes

The effect of motions applied to a wider range of carton models was also analysed, leading to the determination of a set of generic motions. These were classified as "driving" and "guiding" motions.

4.1 Driving Motions

Three types of driving motions were identified using the approach described above, as shown in Figure 9. As well as the grounded folds previously described, subsequent "flap folds" around either a horizontal or vertical axis were identified. These are needed to form additional features such as flaps, lids or double-walls.

The grounded fold has only one key variable (aside from the position of the crease-line in the ground plane), and this is the end angle of the fold. Therefore this type of fold may be produced by a single degree of freedom mechanism (although, in the case of a reconfigurable system, such a mechanism would have to be repositioned for different carton configurations to cope with changes in the position of the fold line). For the flap folds, the height of the crease-line and the start angle of the fold also vary, depending upon the carton configuration.

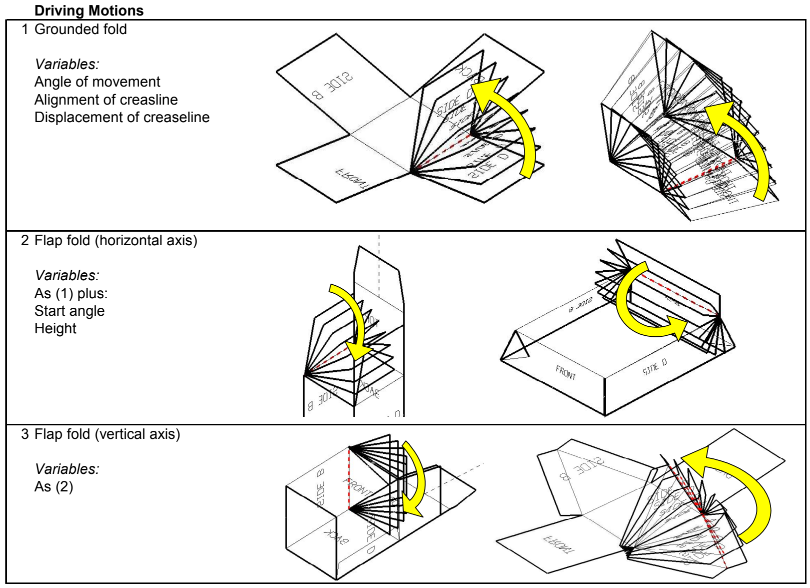

Figure 9. Generic driving-motions for carton forming

4.2 Guiding Motions

As well as the guiding of corner gussets and gable sides described above, two additional forms of guiding motion were identified, as shown in Figure 10. These both relate to tucking a locking tab (attached to the lid) into a slot to keep the carton closed. Due to the synchronisation required between the folding of the lid and the tab, the fold line for the tab moves in an arc. This means that, unlike the guiding of gussets, these tucking operations cannot be achieved with a single degree of freedom mechanism.

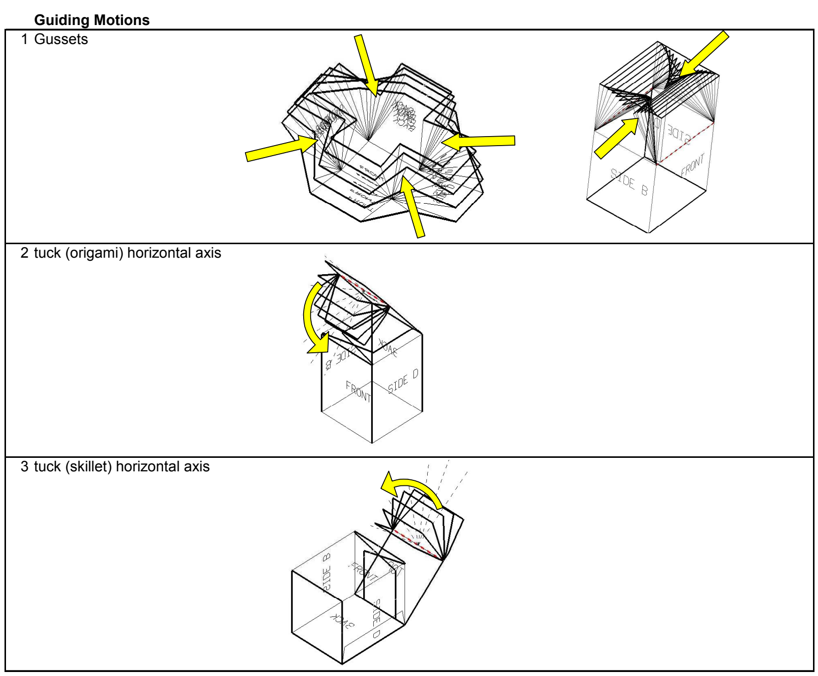

Figure 10. Generic guiding-motions for carton forming

5 MECHANISM SELECTION

Following the approach described in Section 4, the model enables the motion requirements of the carton forming system to be defined. In particular the complexity of those motions can be established, for example, in terms of the number of degrees of freedom they possess. This permits the search for a design solution to begin. The solution may take the form of a mechanism such as a four bar linkage (or even simpler). Using the model to evaluate this solution, the limits of motion for a particular carton can be identified as well as the actual motion itself which is required in order to control the mechanism appropriately. In the case of a reconfigurable system, the motion requirements over a range of cartons of a particular type can be determined and used to ensure that a particular mechanism has the capability to encompass the entire range. Information about the cycle times for each carton can also be generated. If a pre-existing mechanism is already available, the simulation can be used to determine the optimal position for setting it up for a particular carton size. As a particular example, a "folder" mechanism has been created to produce grounded folds. A prototype version is shown in Figure 11.

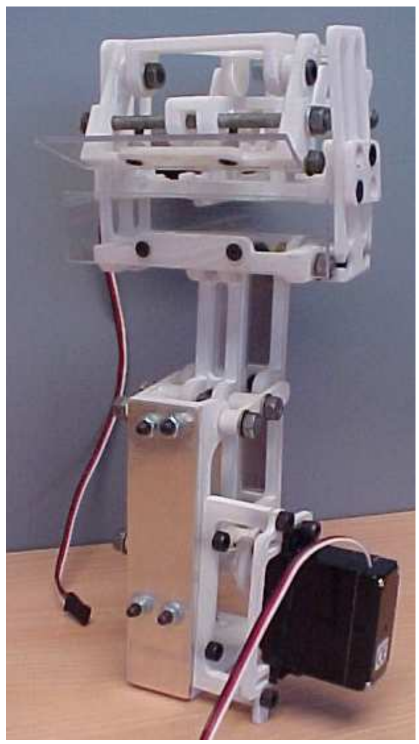

Figure 11. Early folding mechanism prototype

6 CONCLUSIONS

It has been seen that the types of modelling approach used to assemble and simulate the motions of mechanisms and machines can also be used to simulate the formation of cartons used in packaging. It is also possible to form such carton models and their simulations parametrically. This allows a greater understanding of the formation process and the limits and controls required to achieve it.

The motions of the panels of the carton lead naturally to the motions required of the parts of the packaging machine required to perform the formation. In the case of reconfigurable packaging systems, the identification of these motions (and their degrees of freedom) provides initial information for the design of the required mechanical actuators. If such actuators already exist, then the simulation can be used to find the optimal positioning and interrelationship of these, and to obtain their motion requirements in order to specify the control of their movement.

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