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Complex Carton Packaging with Dexterous Robot Hands

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1. Introduction

Product packaging is one of the key industrial sectors where automation is of paramount interest. Any product going out to the consumer requires some form of packaging, be it food products, gift packaging or the medical supplies. Hence there is continuous demand of high-speed product packaging. This requirement is dramatically increased with seasonal consumer products and fancy gifts, which invite innovative designs and attractive ideas to lure the potential customers. Typically such products are delivered in cardboard cartons with delicate and complex designs. Packaging of such designs is not only tedious and challenging but also time consuming and monotonous, if manual methods are employed. For simple cardboard packaging fixed automation has been in use by dedicated machines along a conveyor belt system, however, these machines can handle only simple type of cartons; any change in shape and structure cannot be easily incorporated into the system. They require, in most cases, a change of more than 40 points (Dai, 1996a) to fit into the same type of carton of different dimensions, which means one specific type of cartons requires one packaging line. Capital expenditure increases with the change-over (Dai, 1996b) from one type to another type of carton folding assembly lines. Thus the flexibility is lost due to these limitations and the associated cost in the change-over. This research demonstrates the feasibility of designing a versatile packaging machine for folding cartons of complex geometry and shapes. It begins by studying cartons of different geometry and shapes and classifying them into suitable types and operations that a machine can understand. It conceptualizes a machine resorting to modeling and simulation that can handle such cartons, and finally developing the design of the packaging machine. It has been shown that such a versatile machine is a possibility, all it requires is miniaturization and investment on its development when such machines could be a reality. However, for practical implementation considerations need to be given for a compact, portable system incorporating sensors. The presented design is unique in its existence and has been shown to fold cartons of different complexity.

2. Design Requirements and Principles

Historically, manual methods have been used to complement adapting to different types of carton with changing styles. It takes about 10% of the work order and is called upon as assembly lines to take the order of promotional products. However, problem still exists with the manual lines with a large learning curve for both supervisors and operators, and with inconsistency and

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labor injuries mostly due to hand twisting motions. Further, the manual line is generally considered to be the seasonal force that a dedicated machine still has to be used on a year-run basis to save cost and time. To make the task more difficult, the carton designers must pursue fantasy and originality in carton packaging to respond to a highly competitive market. The frequent change of style and types of carton and the small batches of production present a challenge to the carton assembly and packaging line, and demand a flexible machine to be designed. The onus is thus placed on the packaging industries to fully speed-up the change-over process for different types of carton with the aid of programmable and reconfigurable systems. Development of such agile and highly reconfigurable systems requires systematic analysis and synthesis of each component, i.e. cartons and their folding patterns, machine operating on them, and the complete assembly operation itself. One such approach (Lu & Akella, 2000) has been reported for folding cartons with fixtures. Whilst this approach generates all folding sequences for a carton, the implemented work just handles a simple rectangular carton for which fixed automation is already in place. For cartons of complex geometry, however, synthesis of both the carton and the folding mechanism needs to be considered together to achieve flexible automation in the assembly line. Extensive study has been undertaken by the authors on the operation of complex cartons folding pattern and its sequence analysis, resorting to graph theory, screw theory, matrix theory and representing cartons as a spatial mechanism; thereof studying the mobility and configuration analysis of the carton (Dai & Rees Jones, 1997a-c, 1999); (Dubey et al. 1999a-c, 2001). This chapter presents the research undertaken to design a reconfigurable carton folding machine from design inception to the applications that can handle cartons of complex geometry and shapes.

This project was on the persuasive wish-list of many cosmetic and perfumery suppliers like Elizabeth Arden® and Calvin Klein® and has been under active consideration by the Unilever Research UK for several years. They were willing to support any research ideas to find some alternative means for automating the entire packaging process of fancy cartons, if at all it was possible. As a result the project was jointly sponsored by the UK and the Dutch Unilever consortium to explore the feasibility of developing a flexible packaging machine that can handle variety of cartons of different shapes and sizes. The research began with the study of manual packaging process to reveal that a higher degree of dexterity is required as we move from cartons of simple types to a complex one (Dai, 1996a). Such cartons are formed on a pre-broken cardboard sheet of different geometrical shapes. As the sheet is broken, it has a number of movable panels that can be rotated about the lines of crease. These crease lines facilitate the folding thus resulting in a shape transformation. Figure 1 shows an example of a fancy carton, which after folding, takes the final shape of the 'boy-scout-tent'; generally manual processes are resorted due to the complexity and typically small batch run of such cartons.

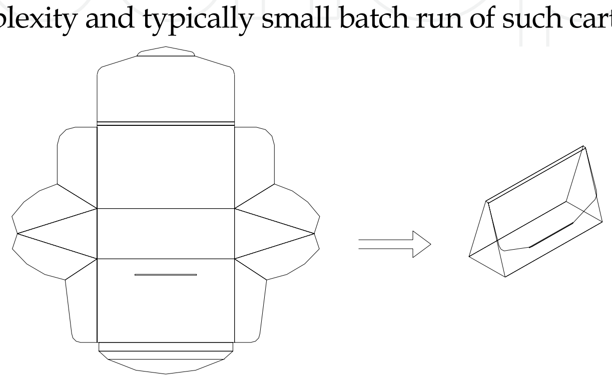


Fig. 1. Shape transformation in a fancy cardboard packaging.

In the manual process of packaging the side panels are bent using fingers since it requires folding along three axes as shown by the arrows in Figure 2, whilst the top and bottom panels are bent using the palms, shown by the flat jaws. The arrows representing the fingers apply a pointed force called 'poking' to the panels while the flat jaws apply 'pushing' forces. At the intermediate level of closing, fine motions are required by the fingers to cross-lock the panels by inserting the projected panels into the slitted areas called the 'tucking' operation.

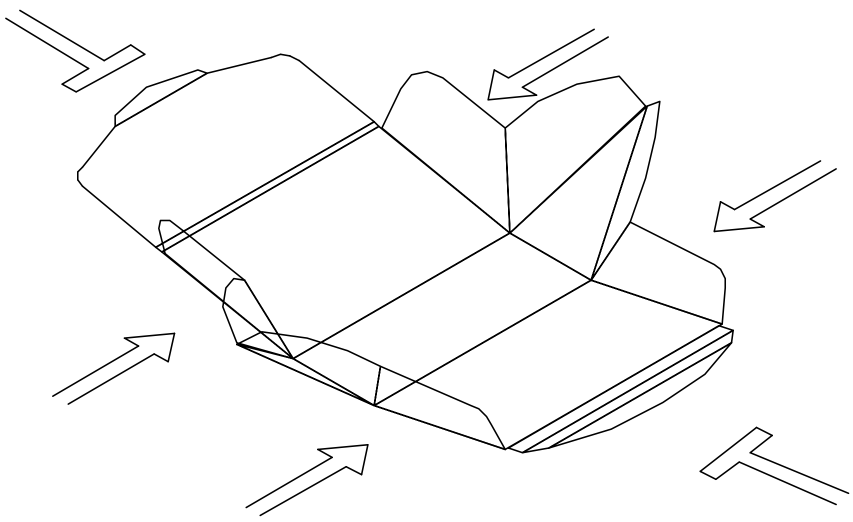


Fig. 2. Manipulative Forces in manual packaging.

In order to generalize the folding process, study of various cartons geometries were conducted that led to the following classification as shown in Figure 3; it also shows various operations involved in cardboard packaging. It is important to note that most cartons have to pass through the three stations of erection, insertion and closure, however, except for the tray-type cartons, the closing stations in other cases involve various manipulative functions (some of which are indicated above), depending on the complexity of the carton geometry.

For designing a mechanical system to erect and fold such cartons the following points need to be considered:

- Multiple functions: to provide various manipulative functions including poking, tucking, squeezing and twisting operations.
- Dexterity: to reach the manipulative positions in different ways.
- Minimum number of axes to control: to reduce the complexity of the system.
- Reconfigurability: to handle variety of foldable cartons with different geometrical configurations.
- Programmability: to control motions on many axes simultaneously and sequentially.

A flexible system to provide fine motions and manipulative functions requires that articulated finger-like links be used. The reconfigurability of the system to handle cartons of different shapes and sizes can be ensured by mounting such fingers on a movable base, such as XY-table or circular tracks. The architecture of the controller should be capable of moving each axis independently. The design should provide all manipulative functions to the fingers without making the system complex, thus resulting in a cost effective solution.

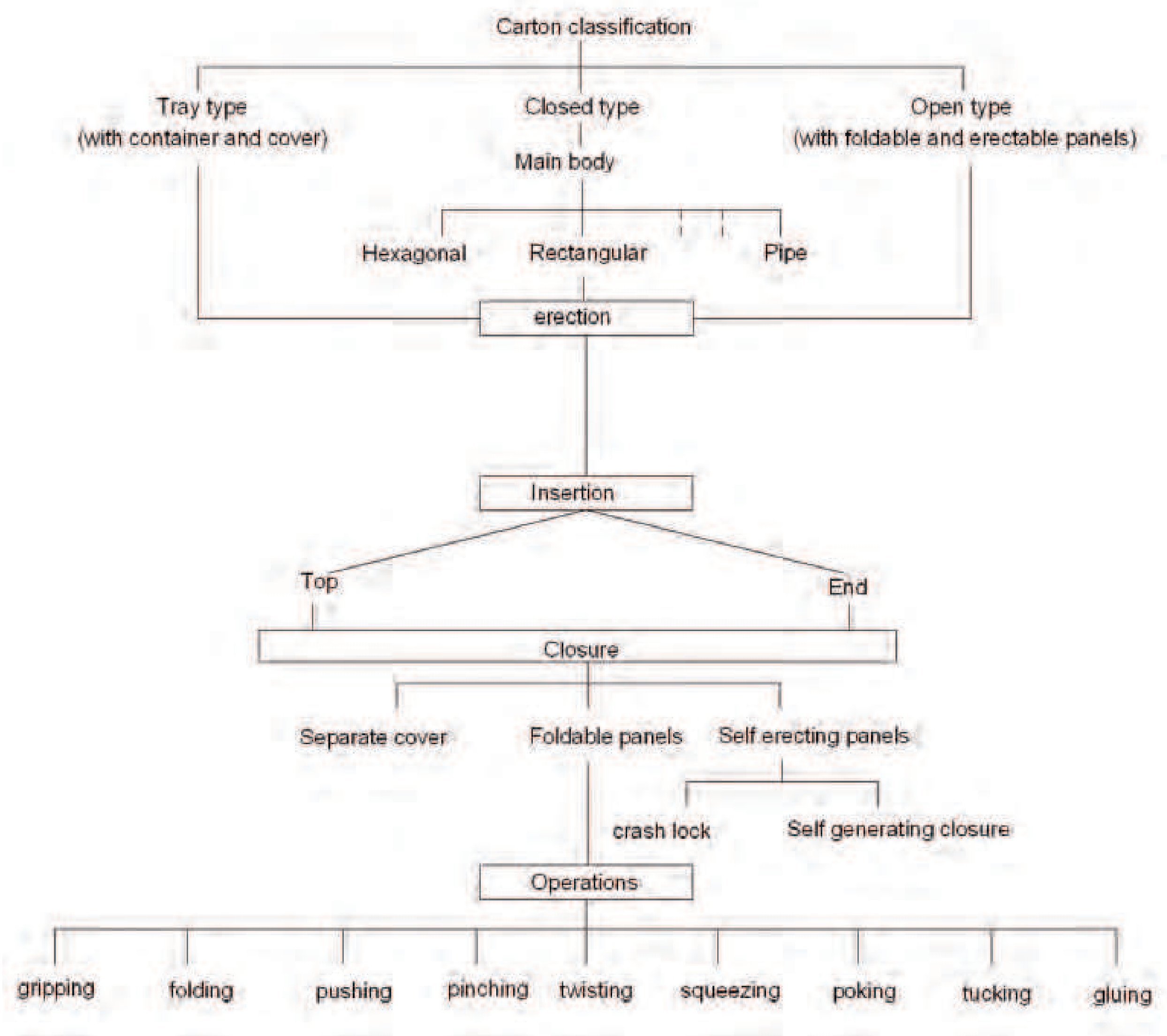


Fig. 3. Operations involved in cardboard packaging.

3. The Conceptual Design

The conceptual design based on the above criterion is shown in the Figure 4 (Dubey, Dai and Stamp 1999a). The design has four fingers, two with three degrees of freedom, and two with two degrees of freedom each. The three-degree-of-freedom fingers provide a yaw (Y) motion at the base and pitch (P) motions on the following two joints forming a Y-P-P configuration. The two-degree-of-freedom fingers have only pitch motions allowing it to move on a planar surface. These fingers are mounted on linear tracks that can move orthogonally and can be oriented at any angle at their base. Two horizontal jaws shown in the figure are arranged with the pushing direction parallel to the fingers' horizontal tracks. The plates attached to the jaws and are to be mounted on passive joints that are under-actuated i.e. during the pushing operation, they can orient along the shape of the cardboard panels. The base of the system, on which the carton is attached, has a circular turntable that can rotate as well as move vertically up and down, thus allowing any orientation and elevation of carton to be achieved that may be required during the packaging operation. These considerations were specifically based on providing high degree of reconfigurability with minimum number of axis to be controlled. The design as conceptualized is based on agility and versatility of the human hand which is capable of performing variety of dexterous functions.

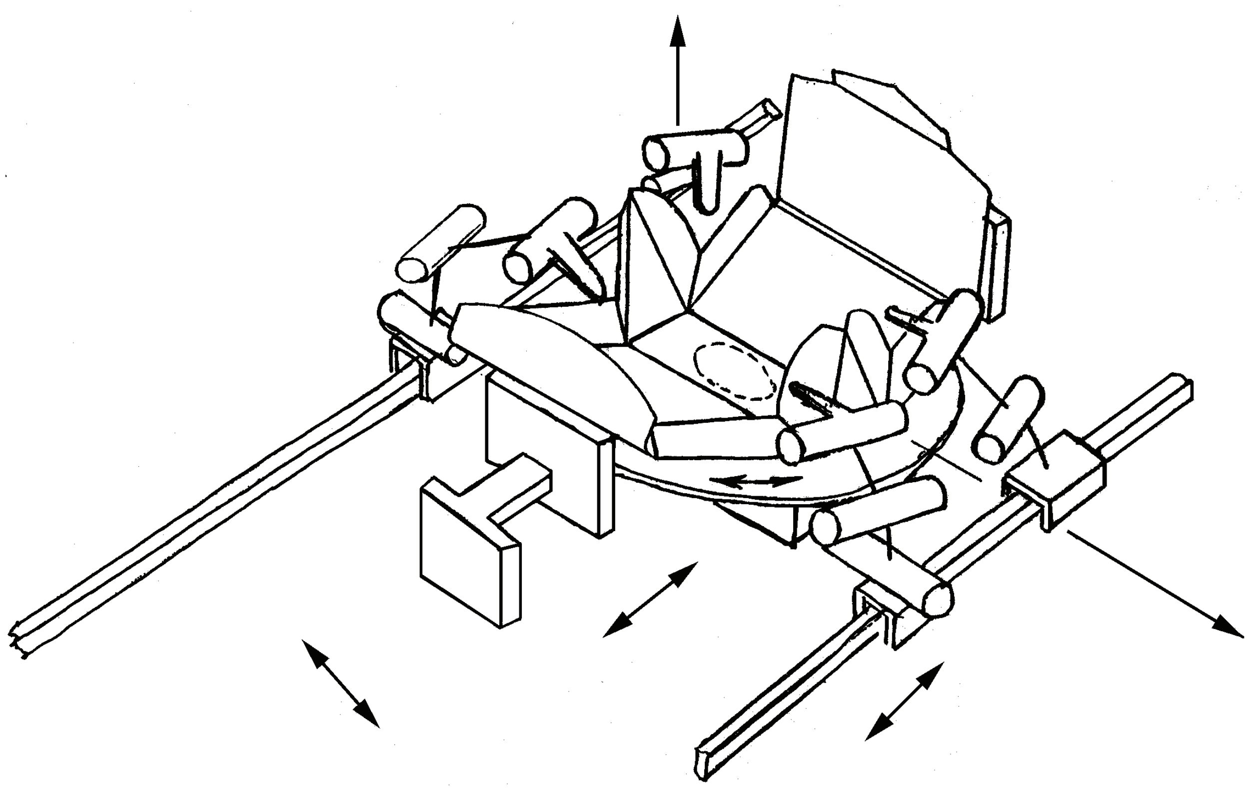
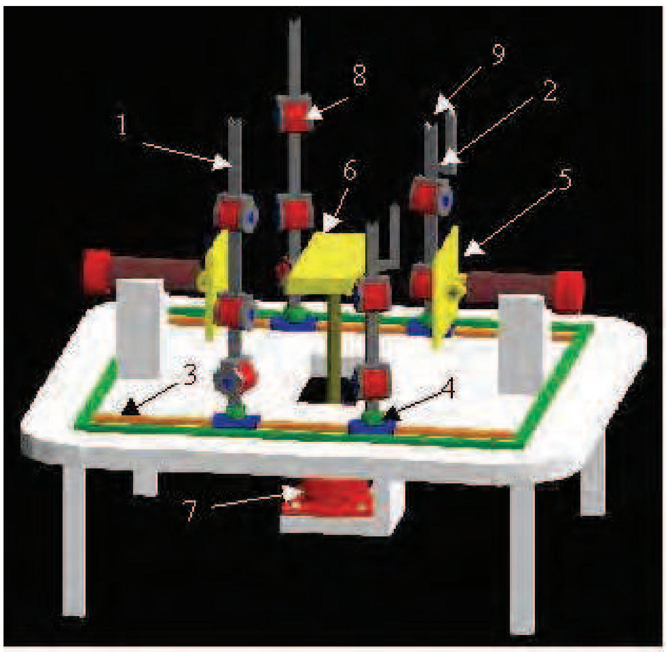


Fig. 4. Conceptual design of the packaging machine.

Based on the conceptual design a model was developed in a robotic simulation environment (Workspace4, 1998) with fingers and horizontal pushers as shown in Figure 5. The base of the small rectangular table at the center, which holds the carton is shown to be actuated by a single motor for vertical movement as well as for the rotation of the table, however, in actual system these two axes will be controlled independently. As far as simulation is concerned, this model will provide all the kinematic information that may be required to run the machine. The fingers are seen to be mounted on tracks, which can slide along the track and the track itself can move laterally. Further the fingers are mounted on swivel-base that allows these axes to be oriented suitably. The joints of the fingers are actuated directly by joint-motors and the whole system has 14 controlled axes. Special considerations have been given to design the fingertips, since they are required to perform various manipulative functions as discussed in the previous section. Inspired by the manual packaging processes, fingertip design incorporates pointed tip with V-groove to apply 'poking' and 'squeezing' effort to the cardboard panels as required in the tucking operation. The pointed tip is used for poking operation while the V-groove holds the common crease line between the panels for squeezing to allow the panels to open up for the tucking operation. The Y-shape of the two-degrees-of-freedom finger is to provide occasional pushing force on flat panels in addition to the poking and squeezing forces. Thus the design can provide the flexibility of offering many manipulative functions with limited degree of freedom to handle different types of cartons in different configurations.



1. 3 DOF Finger
2. 2 DOF Finger
3. Movable Track
4. Finger's swivel base
5. Horizontal jaw plate
6. Rectangular base
7. Base motor
8. Joint motor
9. V-groove/pointed fingertip

Fig. 5. Model of the packaging machine.

4. Simulation of the Packaging Process

In order to simulate the packaging processes, kinematic model of carton as well as packaging machine components (fingers, pushers and the turn-table) need to be developed and integrated together. The kinematic model of the carton has been studied (Dubey et al., 1999); (Dubey & Dai, 2001), which is governed by two basic angles (β and γ) as shown in the Figure 6, and the following equations (1-2) result.

$$\beta = cos^{-1}\left(\frac{R_1\, C\phi - R_3\, S\phi}{C\alpha}\right) \tag{1}$$

$$\gamma = cos^{-1}\left(\frac{(R_1\, S\phi + R_3\, C\phi)C\alpha\, S\beta + R_2\, S\alpha}{S^2\alpha + (C\alpha\, S\beta)^2}\right) \tag{2}$$

where,

$$R_1 = (C^2\delta\, V\theta + C\theta)C\alpha - C\delta\, S\delta\, V\theta\, S\alpha\,,$$

$$R_2 = (S^2\delta\, V\theta + C\theta)S\alpha - C\delta\, S\delta\, V\theta\, C\alpha\,,$$

$$R_3 = S\delta\, S\theta\, C\alpha + C\delta\, S\theta\, S\alpha\,,$$

$$V\theta = (1 - C\theta)\,,\ S = \sin\,,\ C = \cos\,.$$

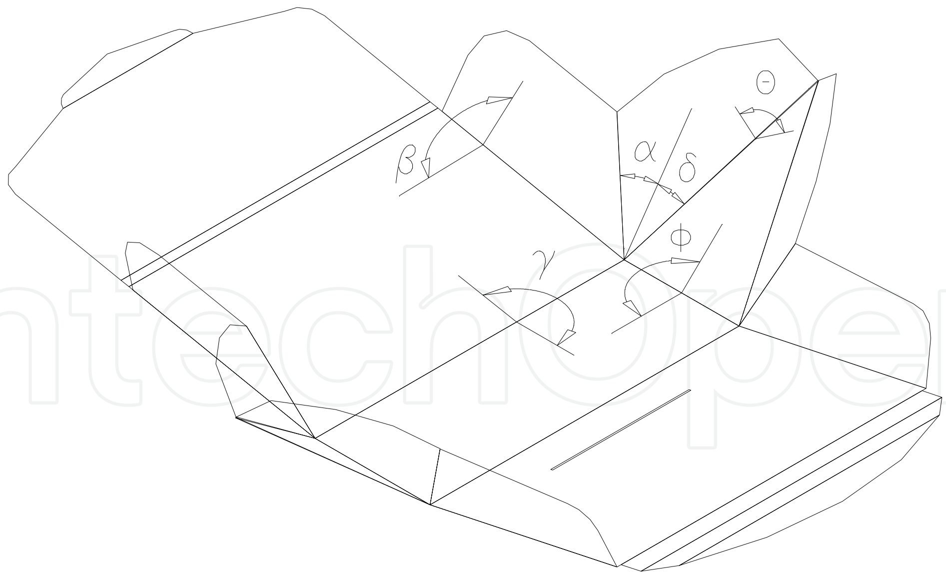


Fig. 6. Defining the kinematic model of the carton.

These equations completely define the folding sequence of the panels for proper shape transformation. If the folding of the carton is to be achieved by a packaging machine, each movable element of the machine needs to be connected kinematically. This requires inverse kinematic solution of the fingers to be developed. The 2-dof planar finger has standard solutions available (Fu et al., 1987), but solution for the 3-dof fingers with Y-P-P configuration is not very common; the closed form solution for which is given by the following equations (3-5), which need to be implemented into the controller for tracking the carton-panel movement.

$$\theta_1 = \tan^{-1}\left(\frac{p_y}{p_x}\right) \tag{3}$$

$$\theta_3 = \cos^{-1}\left(\frac{p_x^2 + p_y^2 + p_z^2 + l_1^2 + 2l_1(p_x\, c_1 + p_y\, s_1) - l_2^2 - l_3^2}{2l_2\, l_3}\right) \tag{4}$$

$$\theta_2 = \sin^{-1}\left(\frac{(c_1\, l_2 + l_3\, c_1\, c_3)p_z - (p_x - l_1\, c_1)s_3\, l_3}{(l_2 + l_3\, c_3)(c_1\, l_2 + l_3\, c_1\, c_3) + l_3^2\, c_1\, s_3^2}\right) \tag{5}$$

where px, py, pz are the co-ordinates of the target point, c and s are sine and cosine of the angle, l1, l2, l3 are the link lengths of the finger corresponding to joint angles θ1, θ2 and θ3 moving from base to the tip.

The kinematic connectivity between carton and the fingers can be achieved by locating various contact points on the carton and recording the displacement of these points as the folding of the carton takes place. The contact points on the carton can be identified by geometrical interpretation of the folding sequences (Dubey & Dai, 2001). These contact points are then used to find joint displacement for each finger's joints. The displacement data are further interpolated to generate optimal finger paths minimizing the unwanted fingers motion and thus reducing the packaging cycle-time. The interpolated data from the simulation can be downloaded to drive the actual fingers. This whole packaging process can also be automated based on the study of the geometric features of the panels and their folding sequences without resorting to the simulation of the carton; this is our current research effort. The model provides all the kinematic information that may be required to run the machine (Dubey & Crowder, 2003). A parametric model of the packaging machine was developed in the software (Workspace4, 1998) that allows geometrical and dimensional alterations in the design to be easily incorporated including the configuration verification. This also allows kinematic parameters of the machine-components to be ascertained before the actual fabrication.

Figure 7 shows the fingers tracking the contact points over the carton while it is folding. The simulation provides many valuable information for design as well as control of the packaging machine. For example, the simulation can be used for geometric as well as configuration checks before deciding on the dimension and structure of the machine. Any new geometrical information of the machine components can be directly obtained from the model by just making parametric changes in the basic dimensions of the model. Motion-data and trajectory of the fingers so obtained during folding of the carton panels can be used for finger control in the actual system. Currently the motion parameter available from the simulation has not been directly integrated to the actual controller thus the data has to be fed off-line in the form of a data-file. Nevertheless, this technique allows full validation of folding sequence and then downloading of these data to the controller.

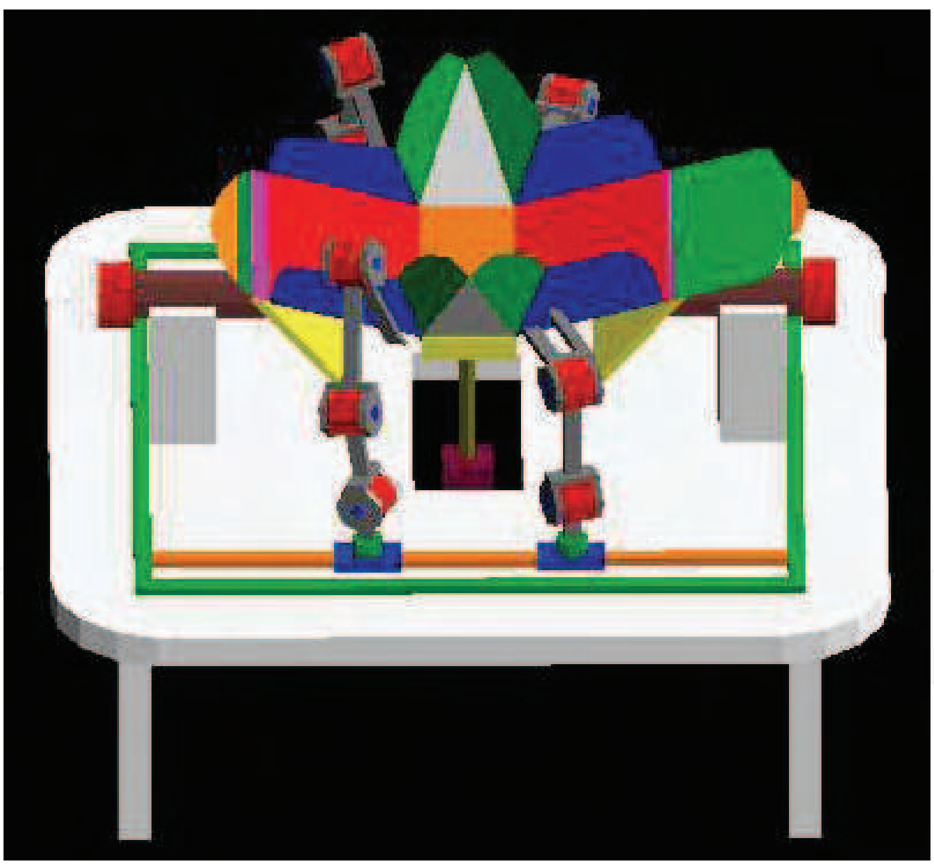


Fig. 7. Carton folding operations with the Fingers.

5. The Packaging Machine

Using the dimensional information from the simulation the packaging machine was developed which uses three linear motors; two for jaw-pushers and one for the vertical motion of the turn-table (Dubey & Dai, 2006). Ten high torque, high performance motors were used on the finger joints supplied by the Yaskawa Motors®, Japan, specifications of these motors were:

Dimension: □30□30 mm
Weight: 70 grams
Torque: 0.7 Nm at 22.5 rpm
Gear ratio: 80:1, harmonic drive

Optical encoder with 96 pulse/rev.

This means a 10 cm long arm connected to the motor can apply a fingertip force of 7 N, which is high enough to fold the cardboard panels along the crease lines. The controller architecture of the system is shown in Figure 8. It has four motion control cards and each can control up to 4 axes (Dubey & Crowder, 2003). These cards are supported by motion control library in C-programming language; it also has a G-code programming interface for quick trial and running motors in teach-mode. The system also incorporates pneumatic connections for attaching suction cups, which can be activated in ON/OFF position by the controller. Currently this is employed to move the turntable from one orientation to the other and to hold the carton in fixed positions, however, at later stage it is planned to use these cups on the fingertips as well, for astrictive mode of grasping. This will have an advantageous effect in handling flat carton panels without any slip (Dubey et al., 1999).

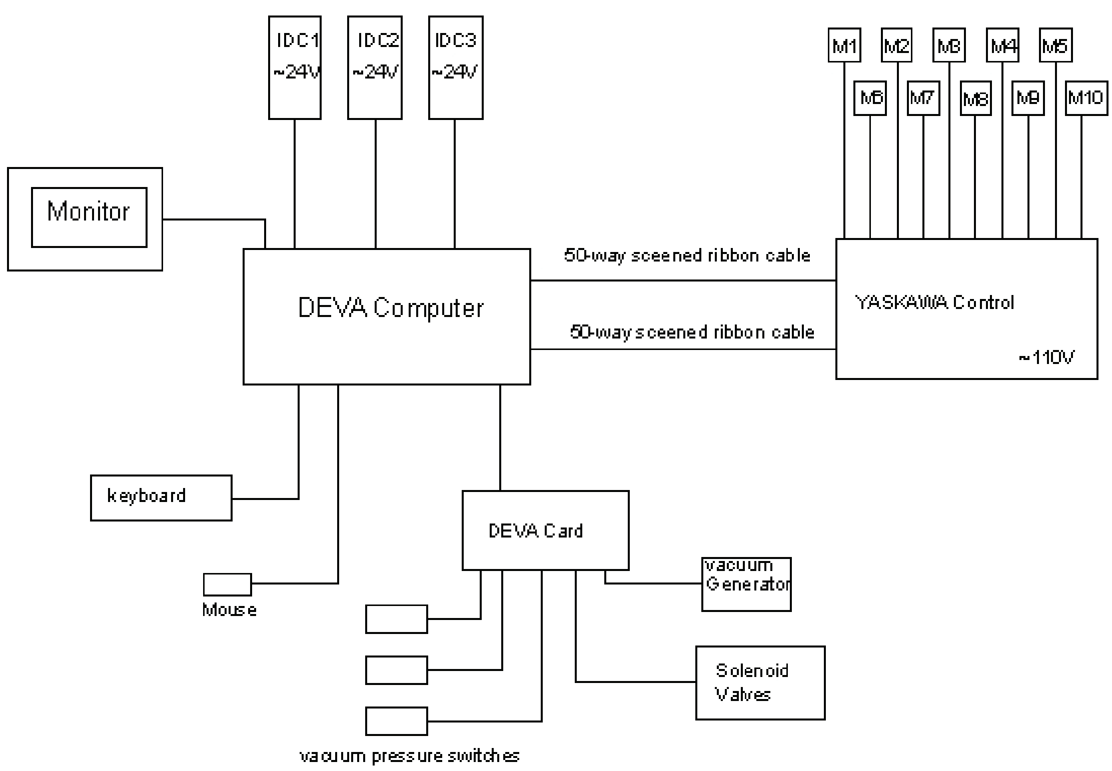


Fig. 8. The controller architecture.

In order to establish the capability of the packaging system for performing erection and folding of cartons, the data-file generated from the simulation was fed to the controller after ensuring that the both model and the machine have geometric and configuration equivalence. The data-file contains the motion data in a single row for simultaneous operation of the motors, whereas the succeeding lines have next stage motion control parameters. Accordingly, the controlling program reads the data file sequentially and generates appropriate interrupts within, to pass the motion commands simultaneously. Thus the fingers can duplicate motion in parallel as well as sequential modes. The programming capability of the controller can be further enhanced by developing sub-routines specific to various manipulative functions, thus allowing modular structure of the controller to be achieved, which can be easily adapted to any new carton folding and packaging sequences.

Reconfigurability of the system was one of the key issues for which this system was developed. The idea was to use the system to fold different type of cartons with little alteration in the system design. But to achieve this, it is important to ensure that the system is exactly configured as per the developed graphical model and the basic structural set up. To run the machine, the data file is included in the main program and the system is first operated in a stepwise trial-mode to verify the fingers' movement whilst the carton is being folded. Once this is achieved the system is ready for automated packaging. The developed machine is shown in Figure 9 where all fingers and horizontal pushers are involved in a complicated sequence of tucking operation. The system was able to erect and fold the carton (Figure 1) successfully in less than 45 seconds. Although it was difficult to give a comparative timing for manual packaging, we conducted some trial run for the same carton. The manual packaging on average (after learning) took around 60s.

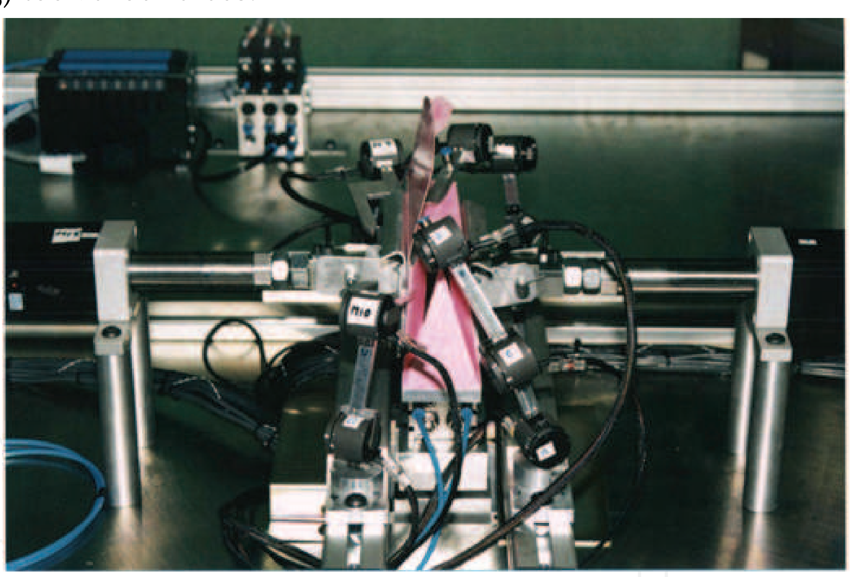


Fig. 9. The packaging machine in action.

Reconfigurability of the machine was demonstrated by folding a second type of carton as shown in Figure 10. This carton is a closed-type of completely different shape and complexity with multiple flaps. This requires various manipulative functions of pocking, twisting and tucking to be performed on the panels. After reconfiguring the structure of the machine, the folding sequences took a cycle time of 45 seconds to complete the carton. The reconfigured machine can be compared with the previous setup in Figure 9. This demonstrates the highly flexible and reconfigurable design of the system.

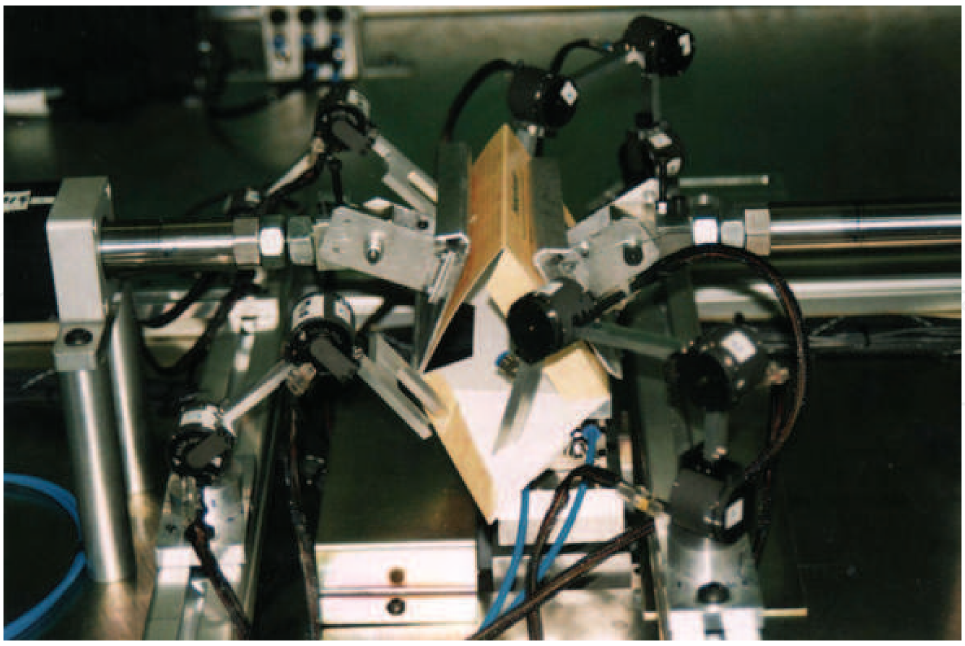


Fig. 10. The packaging machine folding a different carton.

6. Conclusions

The chapter has presented a dexterous reconfigurable assembly and packaging system (D-RAPS) with dexterous robot fingers. The aim of this research was to design a reconfigurable assembly and packaging system that can handle cardboard cartons of different geometry and shapes. The initial idea was to develop such a system that can demonstrate adaptability to cartons of different styles and complexities. It was shown that the packaging machine could fold two cartons of completely different shapes. The cycle time for the folding was approximately 45 seconds in each case. Though this is not an optimized time for folding, it is envisaged to reduce the cycle time to 30 seconds or less with on-line data transfer. Although there are many issues that need to be addressed before a fully flexible machine can be realized on the shop floor, nevertheless, the research was aimed at proving the principle of quick change-over, which faces the packaging industry.

The future enhancement will include optimization of finger trajectory, use of tactile sensors for force feedback to avoid excessive pressure on the panel, and astrictive mode of grasping to involve the vacuum system at the fingertips. It is also proposed to integrate the simulation model directly with the actual machine to download the motion data online. The XY-table can be motorized and controlled for auto-reconfiguration. These advanced techniques will automate the entire packaging process starting from the two dimensional drawing of the cardboard, defining its kinematics then generating the motion sequences leading to the finished product packaging. It is also envisaged to mount such dexterous reconfigurable hands directly onto a robotic arm to offer higher level of flexibility in packaging, if this can be miniaturized. The system will not only perform carton folding but can also be used to insert the product into the carton during the folding sequences. This will reduce the packaging time and will also be able to meet challenges of high adaptability to ever changing demands of high-end personal product packaging.

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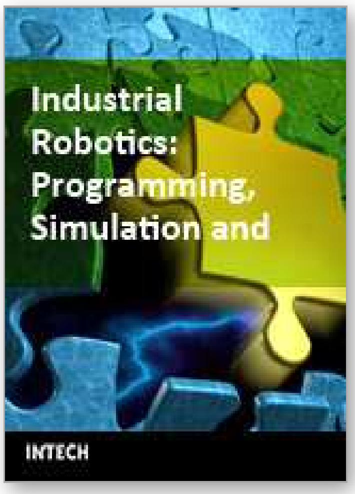

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This book covers a wide range of topics relating to advanced industrial robotics, sensors and automation technologies. Although being highly technical and complex in nature, the papers presented in this book represent some of the latest cutting edge technologies and advancements in industrial robotics technology. This book covers topics such as networking, properties of manipulators, forward and inverse robot arm kinematics, motion path-planning, machine vision and many other practical topics too numerous to list here. The authors and editor of this book wish to inspire people, especially young ones, to get involved with robotic and mechatronic engineering technology and to develop new and exciting practical applications, perhaps using the ideas and concepts presented herein.

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