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Computer-Aided Design of a Mechanism for the Continuous, Automated Assembly of Two Parts at High Speed: A Case Study

Various computer-aided design tools were used to develop alternate designs for mechanisms to assemble two subassemblies of a consumer product on a fully-automated, continuous motion, high speed assembly line. The product geometry required a snap fit and the assembly motion had to be such as to avoid product damage. Four different mechanisms out of a larger number of concepts were developed in some detail and the most promising of those designed for production. All designs involved some combination of linkages and/or cams. This paper describes their design and the use of various CAD/CAE tools in the process.

Introduction

High volume consumer products are often manufactured and assembled on dedicated, hard-automation machinery designed for the specific task. The Gillette Company produces razors and other personal grooming products by these methods in significant quantities (billions per year) at high assembly rates (up to millions per day per machine). The problem described here was provided by Gillette to a group of four senior mechanical engineering students at Worcester Polytechnic Institute as a senior-thesis topic.

Among Gillette's many products are so-called disposable razors, defined as a handle and cartridge assembly, sold attached to one another and destined to be discarded, handle and all, after the blade cartridge no longer performs to the customer's satisfaction. This product is distinguished from their high-end lines such as the Sensor®, Mach3®, and Venus® razors which have reusable handles and disposable blade cartridges.

Disposable razors consist of two subassemblies, a blade cartridge and a handle (Figure 1), each of which has already been independently assembled on its own dedicated machine. These two subassemblies are then brought together in a third machine and automatically joined, in this case with a snap-fit. So the task of the subject machine is to load, orient, assemble, and unload the relevant parts without any human intervention. The production quantities desired for this product made it desirable to create a continuous motion assembly machine to replace the current intermittent motion (indexing) machine used for similar products.

Indexing machines make the machine designer's task much easier because they stop during each part cycle in a dwell to allow parts to be loaded, assembled, fastened together, and unloaded using mechanisms that are fixed to the ground plane. The disadvantage of this type of indexing machine is that their throughput speeds are typically limited to about 200 parts per minute (PPM) due to the dynamics of accelerating and decelerating the relatively large mass of the indexer mechanism.

Continuous motion machines, on the other hand, are capable of much higher throughput speeds, principally because the large-mass components (dials, conveyors, etc.) that carry the low-mass product through the machine are now at essentially constant velocity This allows much higher throughput speeds than with indexers, now limited not by the machine chassis design but rather by tooling mechanism dynamics, part feeding, and part escapement limitations. Simple tasks such as beverage can filling are done on continuous machines at multiple thousands of PPM. More complex assemblies such as razors can be assembled at speeds in the high hundreds of PPM on continuous machines. The disadvantage of continuous motion machines is that the mechanisms that operate on the product must move with the product in order to have zero relative velocity during the operation (e.g., transferring a part). This makes the designer's task more challenging.

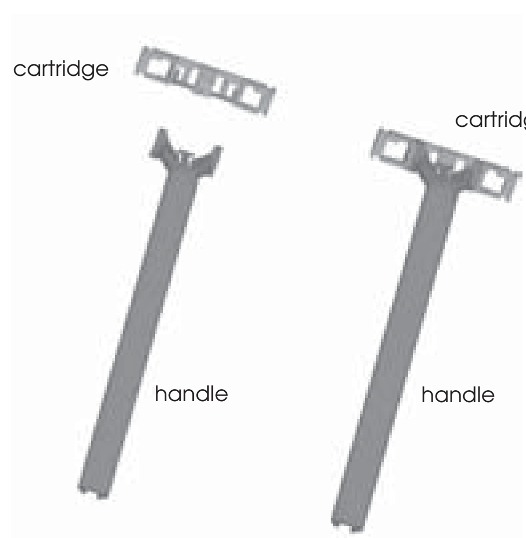


FIGURE 1
A disposable razor

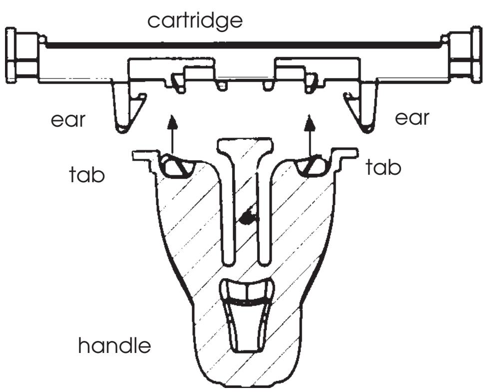


FIGURE 2

Existing assembly motion in an indexing machine

Design Parameters

In this instance, the request was for a mechanism that could assemble the cartridge to the handle at a speed of at least 250 PPM. There exists an indexing machine that assembles this type of product. It holds the cartridge stationary and linearly translates the handle into the cartridge such that both ears on the cartridge are simultaneously deflected by the tabs on the handle as shown in Figure 2. This leads to occasional breakage of the ears on the cartridge. Thus, it was decided to pursue assembly motions that would assemble them with complex relative motion as shown in Figure 3. In this motion, one tab will be tucked under one ear and then the two parts joined by relative rotation, deflecting only one ear with the second tab. Tests done manually on the product showed that this approach reduced the force required to assemble and so should reduce breakage.

The functional requirements for a new design were listed as a set of performance specifications:

A. Assemble cartridges to handles of disposable razors

B. Assemble parts at a speed of 250 parts per minute or greater

C. Have a product scrap rate of 5% or less

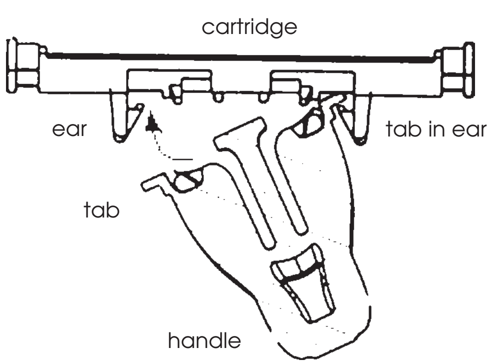


FIGURE 3

Proposed assembly motion in a continuous machine

D. Have a machine efficiency of 80% or greater

E. Last 10 years or longer in 24/7 operation

F. Be completely automated

G. Meet applicable OSHA safety standards

Computer Aided Design Tools Available

The product had been designed by Gillette in the Unigraphics (UG)[1] solids modeling package, and those CAD files were made available to the students. Though the UG package is available at WPI, the students were more familiar with Pro/Engineer[2] and so converted the UG product models to Pro/Engineer. In addition, other CAE tools were used for particular designs at various stages of the design process. These included Pro/Mechanica[3], Excel[4], Mathcad[5], TK-Solver[6], Autocad[7], FOURBAR[8], and DYNACAM[9].

It is the opinion of the authors that, in general, no single CAD/CAE package is sufficient to complete a mechanical design engineering task in the most efficient way. As powerful as each package may be at its particular task, no one package can provide all the functionality that typically is needed for mechanical design; moreover, there is no reason that any one package should do so. Thus, the design engineer must become familiar with a variety of CAE/CAD/computational packages and select the ones that best solve the particular tasks at hand. A combination of synthesis and analysis CAE tools is typically needed, and, for efficiency, their data must be easily transportable among them.

In addition, it is a mistake to believe that CAD/CAE tools are the "be-all and end-all" for all design tasks. There are instances, as shown in this case study, in which the most efficient "design tool" may be a very old-fashioned, manual method such as that of constructing transparent overlays of linkages and/or the creation of simple physical models. These techniques were, in fact, both used to good effect in this project. An atlas of linkage coupler curves[10] is often an indispensable resource as well, and it proved valuable in this project.

Design Concepts

Four basic paths of relative motion were developed to assemble the cartridge and handle. These paths define the relative motion of the components, but do not limit the choice of possible mechanisms to provide them.

Arc and Linear – For this approach, shown in Figure 4a, one of the components moves on a linear path, while the other moves along an arcuate path. Assembly occurs at the point of tangency between the linear and arcuate paths.

Arc and Arc – In this approach, shown in Figure 4b, both components move along arcuate paths. Assembly occurs at the point of tangency between the two arcs.

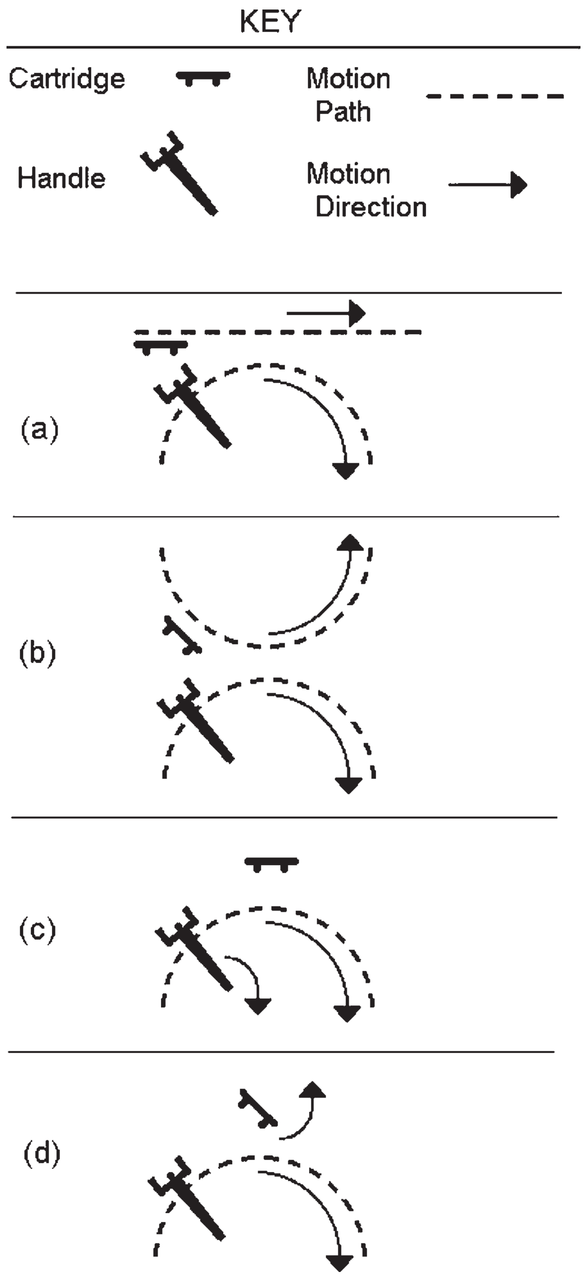


FIGURE 4

Proposed relative assembly motions

Handle Rotate and Pivot – For this approach, shown in Figure 4c, the handle rotates on a large radius in order to mesh one ear under a tab of the cartridge. The handle then stops rotating and pivots about the meshed ear. The cartridge could either be stationary or move in linear translation. Assembly occurs when the second ear of the handle is meshed with the second tab of the cartridge.

Handle Rotate and Cartridge Pivot – In this approach, shown in Figure 4d, the handle rotates on a large radius to mesh one ear under a tab of the cartridge. The handle continues to rotate while the cartridge also pivots about its meshed tab. Assembly occurs when the second ear of the handle is meshed with the second tab of the cartridge.

Of these four preliminary concepts, the first two (Figures 4a and 4b) which have simple relative motions (i.e., either pure rotation or pure translation), proved inadequate to the task. This showed that complex motion of one or both of the parts was necessary to accomplish the desired result. Further iteration of the latter two approaches (Figures 4c and 4d) generated additional variants on those themes.

Many mechanisms were conceptualized to accomplish the desired relative motions. Four potentially viable design concepts chosen from the larger number generated from the concepts in Figures 4c and 4d will now be discussed as representative of the design process and its use of various CAD/CAE tools in their development.

Viable Designs

The four selected "semifinalist" designs in the process were dubbed, respectively, the "Handle Linkage," the "Cartridge Linkage," the "Linear Motion and Rigid Stop", and the "Cam Modulated Slider Crank Linkage." Each will be discussed in turn.

Handle Linkage

This mechanism, as shown in Figure 5, uses the coupler curve of a fourbar linkage to assemble a handle to a stationary cartridge (fed down a stack) as depicted in Figure 4c. The development of the handle linkage began with an attempt to design it directly in Pro/Engineer. This proved difficult because of the high user overhead involved with the creation of links in sufficient detail to satisfy the CAD model constraints, when the basic linkage geometry had yet to be determined. After experiencing some frustration with this approach, the students switched to the "old-fashioned" but well-proven approach of transparent overlays of the cartridge and handle profiles in conjunction with cardboard models of the linkages.

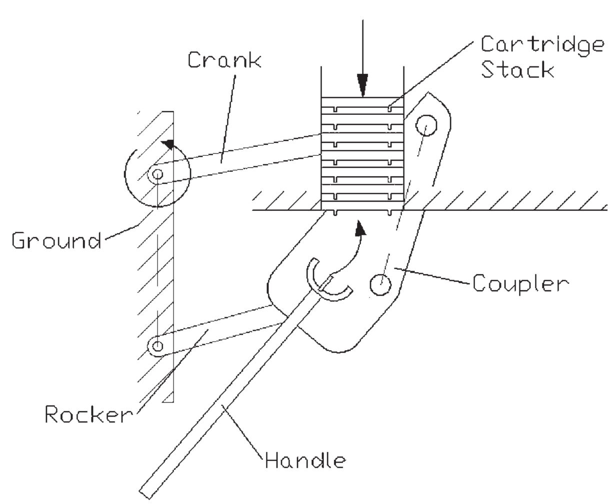


FIGURE 5

Handle linkage mechanism - handle on coupler

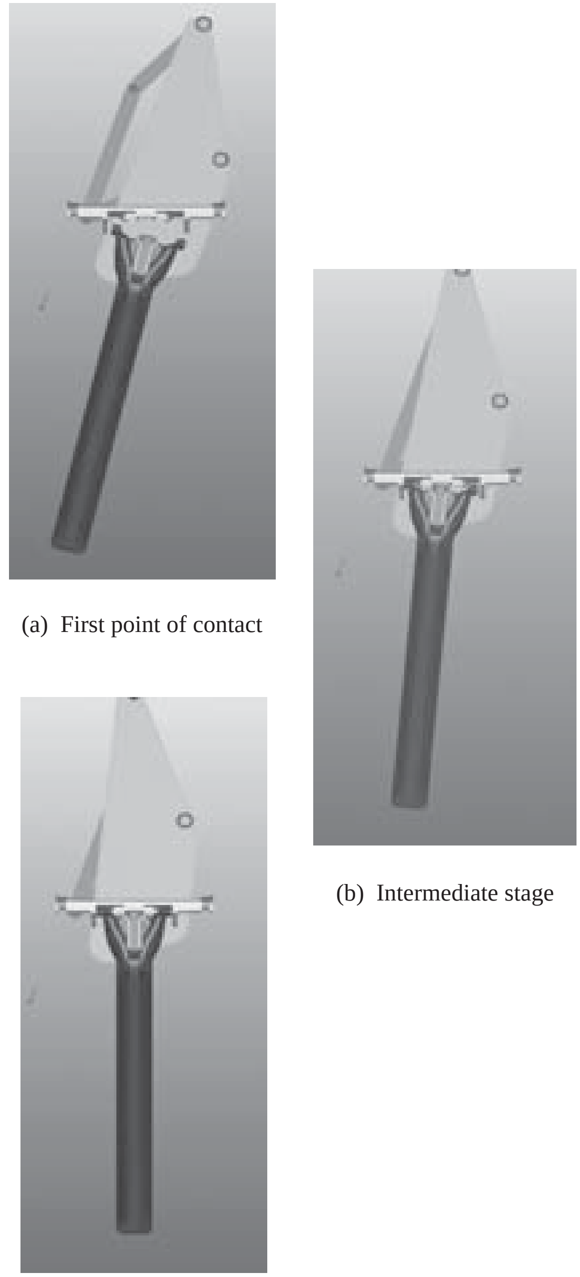
It was determined that the desired complex motion could be created with a fourbar linkage coupler curve containing a cusp. To find an appropriate linkage to create this motion, the Hrones and Nelson atlas[10] of fourbar coupler curves was used. Potential coupler curves were photocopied from the atlas and enlarged so that the transparencies could be overlaid to analyze their feasibility. The transparencies were cut so that the handle profile could be taped to the coupler of the fourbar linkage and then moved with respect to a stationary cartridge. Many cardboard linkage models were created and qualitatively analyzed in order to better understand the motion created by the coupler curves. Program FOURBAR was used to modify the linkage geometry and to view the coupler curves in order to provide a better assembly motion.

The assembly event occurs on a cusp of the coupler curve, so the shape of the cusp was important in achieving a small ear-tab interference. This process was iterated many times to find the best linkage mechanism. With its basic geometry now defined, the chosen linkage could be created in Pro/Engineer with realistic shapes and dimensions. The links were drawn and assembled, and the handle was attached to the coupler link in the appropriate location as determined by the preliminary manual kinematic analysis.

Pro/Mechanica was used to further analyze the kinematics of the linkage with 3D links and evaluate its ability to provide the appropriate assembly motion. This step of the process was important because there were particular features in the 3D models of the handle and cartridge that were not apparent on the 2D overlay transparencies. These features did affect the ability of the parts to assemble properly. However, after minimal revision to the coupler curve, the final assembly motion was found. As can be seen in Figure 5, the cartridge is held stationary in a nest and the handles are delivered to the cartridge on the coupler of a Grashof fourbar linkage. Figure 6 shows a CAD model of the linkage in three positions over its range of motion.

This is as far as this handle linkage design ever progressed because other designs proved to have significant advantages in comparison, for example, the anticipated difficulty in feeding, loading, and unloading the large handle with this design. Handles must be escaped from a feeder mechanism during part of the cycle and fed onto the linkage coupler; the assembly also must be off-loaded during another portion of the cycle. These issues were not addressed in detail for this design and the anticipated difficulties associated with feeding and off-loading the large parts at the rates demanded was one of the reasons that this method was ultimately abandoned in favor of other possibilities.

Nevertheless, digital videos were created with Pro/Engineer in order to present this potential solution to the sponsor at an early stage. It should be noted that the CAD package was very useful for creating videos. If this package had not been available, a fourbar linkage model would have had to be created just to show the potential of its assembly motion in 3D. This exercise pointed out the value of using a hybrid combination of classic manual linkage design combined with the power of state-of-the-art CAD technology.



(a) First point of contact

(b) Intermediate stage

(c) Final position

FIGURE 6

Handle linkage mechanism CAD model in three positions

Cartridge Linkage

The anticipated difficulties of feeding and off-loading the large handle to and from a moving linkage prompted consideration of an inversion of the procedure that would place the smaller cartridge on the linkage coupler. The cartridge linkage mechanism involves moving the cartridge along a coupler curve of a four bar linkage to assemble it to a stationary handle as shown in Figure 7.

A similar process was used to create the cartridge linkage as was used to create the handle linkage. Again, this process consisted of placing transparent overlays onto cardboard linkage models to determine suitable coupler curves for the desired motions. Once a suitable coupler curve was determined, the link lengths generated from FOURBAR were input into Pro/Engineer and created as part files. These part files were then built into an assembly and transported into Pro/Mechanica for motion analysis. The coupler curve was modified using FOURBAR and the new link dimensions were put back into Pro/Engineer and then into Pro/Mechanica. This type of iteration between the three software packages continued until a suitable coupler curve and non-interfering link geometry was created to provide the proper assembly motion. Once the link geometry was finalized, Pro/Engineer was used to create an actual part that would allow for suitable operation without failure. Pro/Engineer was used to create a suitable ground plane and a nest for both the handle and the cartridge. The design appeared to be a suitable solution based on this analysis. A CAD model of this design is shown in Figure 8.

Linear Motion and Rigid Stop

In this design, the handle moves linearly and the cartridge's path motion is along a stationary cam surface, with its ears sticking up as shown in Figure 9. This mechanism is a passive design in that, when a handle contacts a cartridge, the handle tab meshes itself under a cartridge ear and then drags the cartridge past the vertex of the stationary cam. The cam contour provides rotation to the now engaged cartridge and snaps the second ear onto the second handle tab. This sequence is shown in Figure 10.

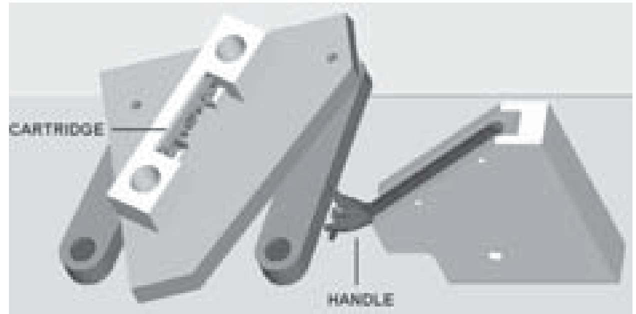


FIGURE 8

CAD model of the cartridge linkage assembly mechanism

The principal problem with this design was that the cartridge blades were in contact with the linear cam surface and so subject to potential damage. In order to prevent this, a 'puck' or carrier must be provided to nest the cartridge. The puck protects the cartridge from damage. After assembly, the razor is off-loaded from the puck and the puck is recirculated and reused

The fact that this system was designed to be passive became an issue when the puck mass was added to the cartridge in order to protect the blades. The resulting impact force when the puck and cartridge are picked up by the moving handle and its nest was believed to be unacceptable. A better solution was to accelerate the puck to approximately the handle's velocity before impact by some means such as a variable-pitch lead screw. This would create a fairly complex system, but one which would be minimally invasive to the parts.

Cam-modulated slider crank linkage design

A possible improvement over the lead screw concept could be a servo-driven slider crank linkage that duplicated the kinematic motions of the passive stationary cam by placing the

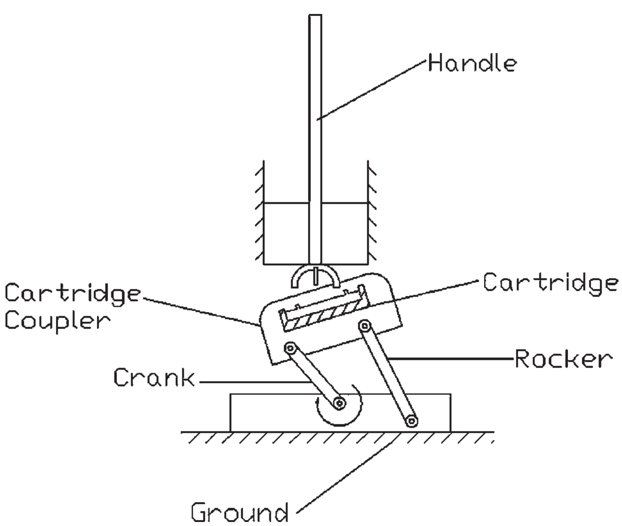


FIGURE 7

Cartridge linkage assembly mechanism schematic

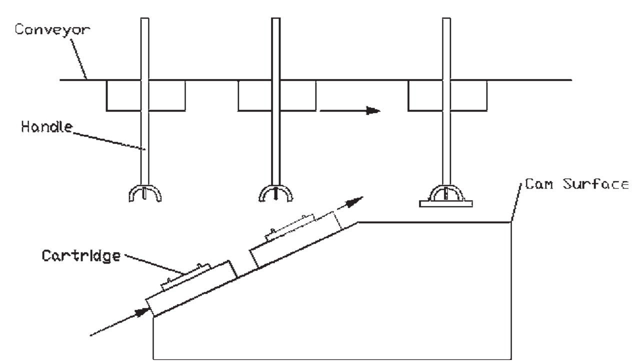


FIGURE 9

Schematic of the linear motion and rigid stop mechanism cartridge on its coupler. This mechanism could also match velocities at contact by variation of input crank velocity during the cycle by suitable programming of the servomotor. In this design, shown in Figure 11, a servo-driven fourbar slider-crank linkage replaces its slider block with a roller follower running in a cam groove. The coupler holds the cartridge in a nest. Changing the contour of the cam track modifies the coupler curve geometry as does varying the link ratios, thus introducing another design parameter in the form of the cam track contour.

Note that, kinematically, the addition of a non-constant curvature slider track effectively makes the slider crank linkage become a fourbar (non-slider) crank-rocker linkage whose rocker's length varies with the radius of curvature of the cam track that guides its coupler-crank joint. The servomotor drive on the linkage crank allows dynamic modulation of the input crank velocity in order to control the velocity of the coupler point independent of the linkage geometry. After assembly of the product occurs, the servomotor reverses, returns to home position and stops while a new cartridge is loaded, still being an intermittent motion.

This was one of the most promising designs up to its time, although it raised several concerns, principal among which was that this was an intermittent mechanism. The servomotor was required to drive the linkage through the transfer motion, stop quickly, return to home for a small fraction of a second while being reloaded, and then accelerate forward again matching velocity to complete another assembly. All this would have to occur four times a second.

As with other designs, part feeding, loading, and unloading difficulties were anticipated with this design. Nevertheless, it was prototyped to obtain data on its assembly performance. This design, in combination with features of the others previously described, led finally to a simple and elegant solution that seemed to satisfy all the requirements of the performance specifications.

Final Design

The first embodiment of this design provided only one station of assembly mechanism as shown in Figure 11. The concept was to oscillate the crank with the servomotor, chasing the continuously moving handle and matching its path using the cam modulation and matching its velocity with the servo. The cartridge motion was successfully arranged to allow the assembled cartridge to cleanly leave its carrier once on the handle by dropping the cartridge carrier away from the handle with the cam contour. The servo would reverse the crank's rotation and quickly return the empty carrier to the load station for another cartridge.

After the linkage and cam geometry was worked out, it became clear that the design lent itself to a multiple-station approach (Figure 12) in which some number of identical cam-modulated fourbar slider crank linkages would be

(a) First point of contact

(b) Intermediate stage

(c) Final position

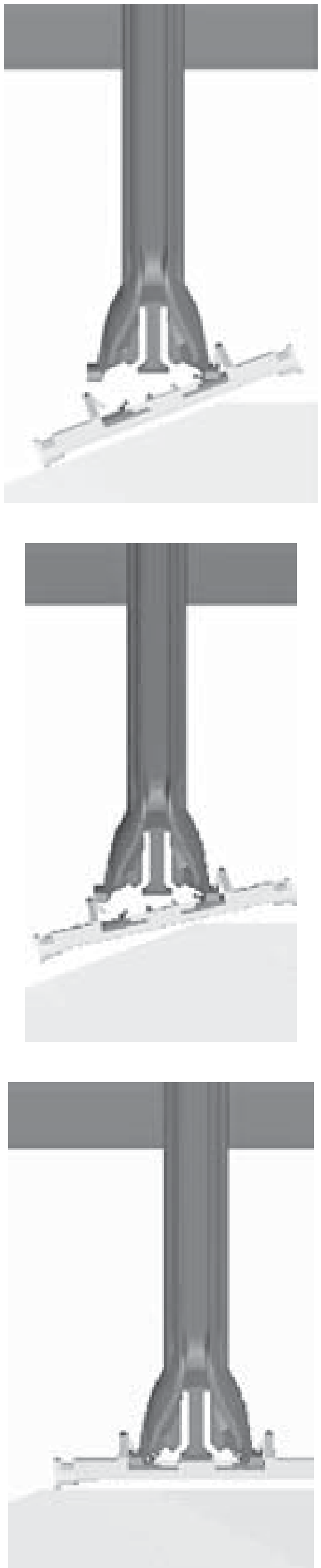


FIGURE 10

CAD model of the linear motion and rigid stop design

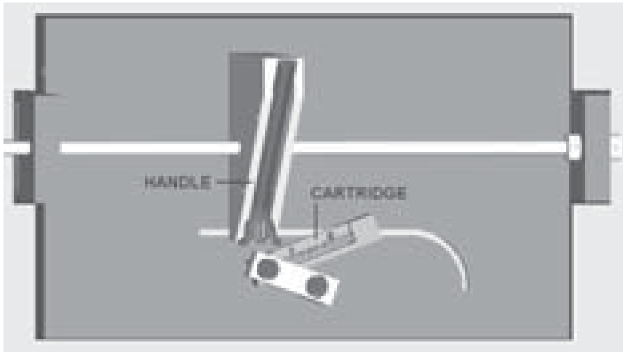


FIGURE 11

Cam-modulated slider crank linkage design (one-up)

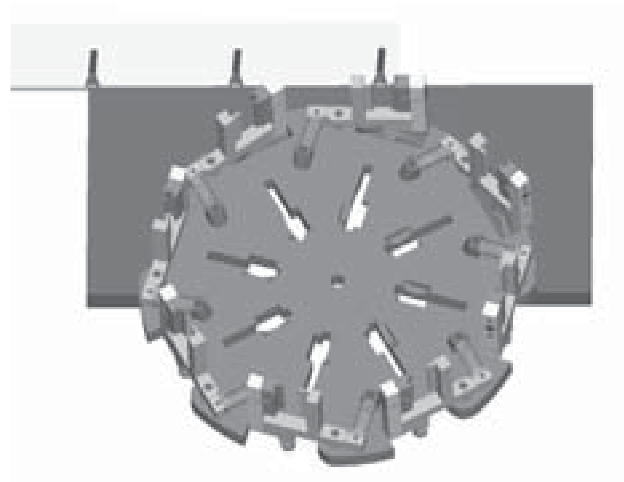


FIGURE 12

Cam-modulated slider crank linkage design (N - up)

mounted on a large diameter rotating dial. The dial would carry them around a stationary cam track that would modulate the path of each linkage station as it passed the handle conveyor. This then eliminated the need to stop and reverse the linkage crank. The dial that carries the linkages is now the common input crank for all (phase-shifted) stations. The dial is driven by a single servomotor that must be programmed to modulate the dial velocity *N* times per revolution in order to match the velocity of the components during assembly. Prior to assembly, the cartridge is at a slightly higher velocity than the handle to place the cartridge ear under the handle tab. The servo then slows the cartridge to match the handle velocity so that the components have equal velocity at the first point of contact.

The cam, in conjunction with the servo driver, provides the proper cartridge position before and during assembly to the handle. Specifically, the cam is designed so that the follower reaches the flat section of the cam prior to the handle. During the assembly portion of the cam, the follower is constrained in straight-line motion, parallel to the conveyor. The coupler motion rotates the cartridge's second ear into engagement with the handle's second tab. The cam then drops the follower down and out of the handle's path to allow the cartridge to cleanly escape its carrier in linear translation with the handle, once they have been assembled. The same stationary cam segment operates all *N* linkages as they pass the assembly station. During the non-assembly portion of the cam, new cartridges are fed to the carriers on the coupler links.

Pro/E was used to draw up preliminary embodiments of how the linkage would be attached to a dial in order to make the crank into a full disk with multiple stations. Programs DYNACAM, Pro/Mechanica, MathCad, TKSolver, and Excel were used to create and test a variety of linkage geometries and cam profiles in order to determine the optimum link lengths and the optimum profile of the cam, which used a combination of polynomials and B-splines to achieve the desired motions with proper control of the higher derivatives. This was done concurrently with the development of the servo driver velocity profile, which though not directly tied to the profile of the cam, is highly dependent on the size of the crank and coupler.

Pro/Mechanica was used to test the cam and driver profiles, to ensure that they produced the desired output. The cam profile from DYNACAM was brought into Pro/E as was the angular velocity profile required for the servo to act as the driving function. The use of this tool, especially for the servo driver, answered many questions about what was necessary to create the desired motion. This proved to be a very valuable tool, as it allowed viewing of the 3D interaction between the handle and cartridge throughout the cycle and made it possible to ensure that there was no interference prior to the assembly point.

DYNACAM was also used to determine the forces on the cam follower as well as other important physical features, specifically the follower spring parameters needed to maintain a resonant frequency higher than the operating frequency. The cam was form closed (track cam), but a follower return spring was nevertheless fitted to keep the roller follower against one side of the cam slot to eliminate crossover shock and improve accuracy.

Cartridge Indexing and Feeding

Along with the cam-modulated linkage design, a separate fourbar linkage was developed to index the dispenser (carrier) that carries the cartridge on the coupler. The cartridges are supplied to the assembly machine in plastic dispenser "trays" that hold 5 cartridges each as shown in Figure 13. To load and feed the cartridges, it was assumed that a feed rail would bring a steady flow of dispensers to the center of the dial from above. After escaping them onto the dial at the stationary dial center, they will be accelerated outward to the proper dial radius and positioned above the coupler of the slider crank linkage at a feed station and then queued vertically on the coupler of each linkage

FIGURE 13

Cartridge dispenser

A means was needed to index each dispenser downward by one cartridge per cycle. The handle removes a cartridge directly from the dispenser pocket, making it in effect the cartridge carrier and nest combined. A straight line linkage was desired to grab the dispenser at the right time, pull it down the right distance, and hold it there while its cartridge is removed.

This provided a challenge to find a linkage capable of indexing all dispensers independently. Program FOURBAR was used extensively for this task with many iterations, as was Pro/E, also iterating between them. In fact, once it was determined that spacial limitations on the driving disk were also a concern, combined with the length of the straight line motion and approximate cusp needed to index the dispenser each cycle, the game became: "Use FOURBAR to find a straight-line linkage, walk to the next computer to build this linkage in Pro/E; test to see where the ground pivots needed to be placed, and ensure that the straight-line portion of the pull-down mechanism was sufficiently long; if not, return to FOURBAR with what was learned from the Pro/E exercise, and make the necessary changes." This process was continued until an optimal linkage design for the dispenser indexer was determined. Iteration not only between designs but between CAE packages was necessary and useful in this design task.

Figures 14 and 15 show the Grashof fourbar straight-line linkage with the coupler curve designed for this task. Its crank is driven by a stepping motor that is programmed to advance the coupler point the requisite distance, hold it in position for the requisite time, and repeat until the cartridge is empty. It then grabs the next full dispenser behind the empty one and repeats the process. The empty dispenser is ejected by air jet. Figure 16 shows an overview of the entire mechanism.

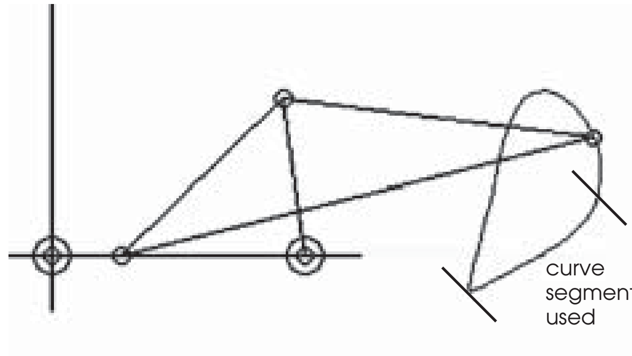


FIGURE 14

Schematic and coupler curve of the indexing linkage

Conclusions

A significantly difficult and complicated machine design task was accomplished in a relatively short time due in part to the availability of a number and variety of computer-aided-design packages. Without these tools and technology, a design could certainly have been accomplished, but its quality would probably have been lower and the time required greater. It is unquestioned that the detailed analysis done of the kinematic and dynamic behavior of the design would have not been possible without the CAD/CAE tools used. Finally, it became obvious that even the most sophisticated of the available CAD/CAE tools are seldom sufficient unto

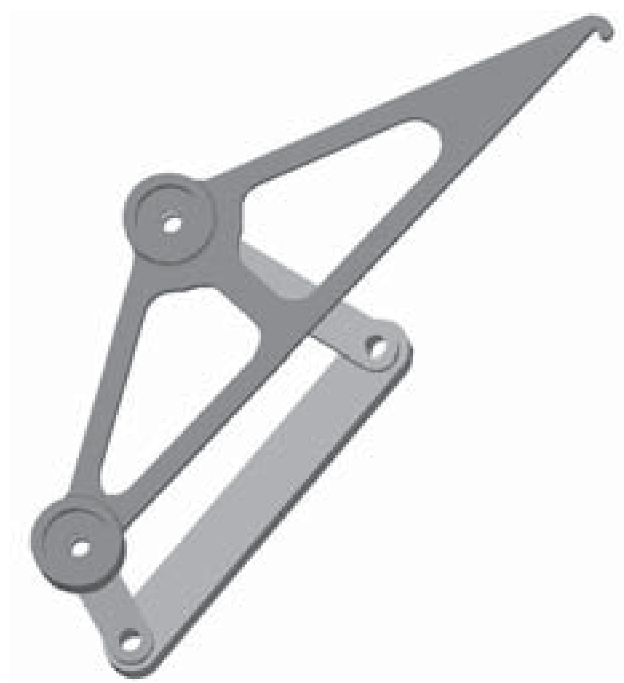


FIGURE 15

Cad model of the indexing linkage

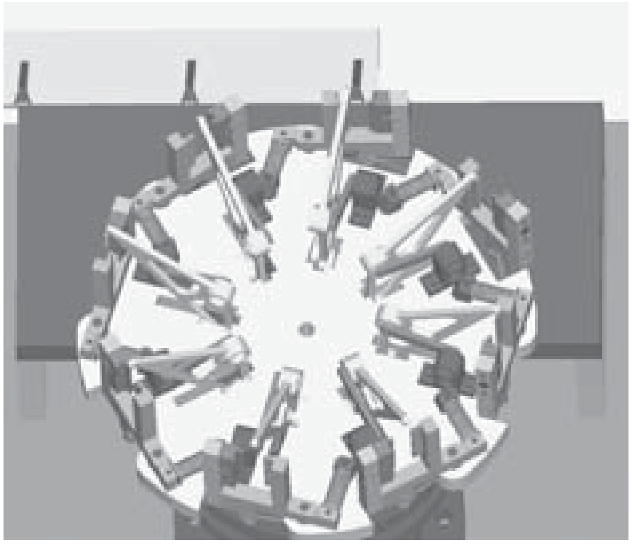


FIGURE 16

The final design

themselves to provide all the design and analysis capability that is needed in a real design problem. Many packages, each with its particular features and strengths, were needed to accomplish all aspects of the design. Not only was iteration within a CAE tool required, but iteration between tools was also needed.

Acknowledgments

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