ABSTRACT: Singulation is the term used by the U.S. Postal Service denoting the removal of a single mailpiece from a stream, stack, or heap of mailpieces. Irregular parcels and pieces is the expression used to represent boxes, rolled newspapers, film mailers, bags, and enveloped flat mail. The task or heap of mailpieces is irregular parcels and boxes. Rolling newspapers are consuming and cumbersome. To expedite the moving conveyor, the work mass is polled from a moving conveyor at 36 pieces/min with more than 95 percent efficiency. The system uses range imaging to guide an AdeptOne robot in removing the parcels from the moving conveyor. The work was sponsored by the Office of Technology Resources of the U.S. Postal Service.

Introduction

In 1983, the United States Postal Service (USPS) began funding research in specific technologies to answer long-standing needs for improving productivity. These needs stem from the labor-intensive processing of oversized letters (flats) and irregular parcels. Currently in existence are procedures for the automated sorting of standard letter- and legal-size envelopes that use optical character reader and document sorting technologies. These technologies evolved in conjunction with the needs of the data processing and banking industries. However, because the automated processing of irregular parcels and pieces is uniquely a post office concern, industrial and business sponsorship has not developed. Clearly, the technical solutions needed to reach the performance goal of 60 parcels/min must be sponsored by the Postal Service.

The current manual process for sorting irregular pieces is time-consuming and cumbersome. The USPS defines an “irregular” as any exception to uniform mail classes, including such extremes as coconuts, automobile tires, and potted palms. Examples of irregular parcels are shown in Fig. 1: in a typical manual processing station in a post office, a conveyor spreads mailpieces dumped from a bin near an operator, who performs five tasks. The operator selects and grasps a single piece (singulation), orients it to expose the address block, locates the address block, reads the zip code, and tosses it into one of 20 to 30 hampers. The work standard for this task is 250 pieces/hr. Because the number of bins for receiving mail are limited, the pieces usually must be sorted again to yield a greater depth of sort. Irregular-mailpiece handling costs the Postal Service about $400 million a year. USPS-sponsored research is in progress on each of the five tasks mentioned.

The General Electric Advanced Technology Laboratory is developing an automated system for singulating heaped irregular parcels and pieces from a moving conveyor. The system uses a high-performance AdeptOne robot for the mechanical task and a range imaging system to measure the parcel shape and orientation so that it can be located and grasped. Other contractors are developing techniques for capturing images from all faces of boxes, flats, and cylinders on a conveyor, and then analyzing these images to locate address labels and read zip codes. Small-parcel sorting machines developed in Europe can be used in principle, in complete automatic handling system.

The task of singulating irregular mailpieces resembles the classic, unsolved, “generalized bin-picking” problem, in which an unpredictable mix of sizes, shapes, and weights must be grasped and removed. The approach described here is intended to lead to a practical, high-performance production system for handling in the 1990s. This system is shown in Fig. 2.

To justify investing in such a system, a significant improvement in productivity must be achieved; that is, increased throughput, freedom from jamming, and reliability at a reduced cost must result from such an effort. The ultimate performance goals set the throughput rate at one article per second, with a singulation efficiency of 97 percent of the total pieces introduced into the system. When compared to the manual sorting rate of 250 pieces/hr, the output of this current system is a very attractive 2100 pieces/hr.

The effort described in this paper has resulted in the development of a system that approaches these goals. Several major components of the system have been designed and implemented. One such accomplishment is a real-time range imaging system and the related algorithms for recognizing, sizing, and locating objects for retrieval. Another is a sophisticated, versatile end-effector that has proved effective in handling highly diverse materials and objects. These techniques have been integrated into a fully autonomous recirculating system, which provides a jam-free, error-compensating flow path for materials being processed. The system accepts irregular parcels and pieces from a filled conveyor and singulates them with high efficiency. The performance of the system is summarized in the Table.

Fig. 1. Examples of irregular parcels.
Fig. 2. Automated system for singulating irregular parcels from a moving carousel.

Table

<table>
<thead>
<tr>
<th>Measure</th>
<th>Actual</th>
<th>Goal</th>
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<tbody>
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<tr>
<td>Maximum parcel weight, lb</td>
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<td>Measured throughput, pieces/min</td>
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<td>Singulation efficiency, %</td>
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</table>

System Overview

The Georgia Tech Research Institute conducted research on the nature of mail streams, which showed that more than 96 percent of the irregular mail can be classified as flats, boxes, or cylinders, and that they fall within a reasonable range in size and weight. An industrial robot such as the AdeptOne has the load capacity, workspace volume, speed, and acceleration to handle up to 88 percent of the irregular mail at the cycle times demanded by this system [1].

The central feature of the system described here is an 8-ft-diam rotating disk, which carries irregular parcels past a range imaging system and a high-performance, SCARA AdeptOne robot. A 56-in.-diam conic section is attached concentrically with the carousel axis to restrict the mailpieces to the outer 20 in. of the carousel. Empty areas on the disk are sensed by an overhead camera, which controls the start-stop operation of the dispensing conveyor that fills these gaps. Mailpieces can overhang the end of the dispensing conveyor without harm. An injection conveyor, following the dispenser, runs continuously to push any piece that falls on it onto the rotating disk so that it cannot hang up and produce jams. Resultant crowding or overlapping does not disrupt the operation of the system. The mailpieces pass through a projected plane of laser light, and a charge-coupled-device camera images the light's profile on the mailpiece and converts it to a flowing high-resolution range image in a special buffer. Frames of this image are snapped and sparsely sampled for high-speed interpretation, following the Tsikos/Frederick method summarized below [2]. From the interpreted images, a list of targets for removal is prepared and transmitted to the AdeptOne controller. The removed items are carried in a singulated stream on a conveyor, which leads to a system for mailpiece imaging and address finding.

The robot's removal of a target mailpiece may disturb nearby pieces. Mailpieces that are not removed recirculate on the disk. Their new locations and attitudes are determined when the disk again carries the mailpieces through the range imaging area. Thus, the system need not perform perfectly in each pass to be effective. For maximum throughput, however, a mailpiece should be available for every robot cycle. Full system capacity is reached when the disk is covered and the robot is in continuous motion.

Although the sizes vary and the mix is unpredictable, all objects can be grasped by compliant vacuum cups targeted to the centroid of the available surface. The robot's end-effector has a cluster of individually controlled vacuum cups, which can be switched from pressure to high-capacity vacuum by control valves mounted on the robot column, as shown in Fig. 2.

Specialized Range Imaging Hardware

The range image is generated as the mailpieces move through a plane of light projected perpendicularly onto the carousel from an overhead laser (Fig. 3). This plane creates a stripe of laser light on the top surfaces of the parcels as they pass through it. Because it is desirable to keep the laser within the eye-safe range, the system has difficulty with dark green, blue, and black mailpieces. This stripe is viewed by a camera from a known angle to permit determination of its height by triangulation (Fig. 4). The camera is adjusted so that the stripe on the empty carousel appears along the far left edge of the camera's field of view and any mailpieces on the carousel deflect the stripe to the right into the camera's view. The amount of this deflection is a function of the contour to the top surface of the mailpiece in the plane of illumination.

Special electronic circuitry digitizes the camera's video signal, encodes stripe deflection information as gray-scale intensity, and buffers the most recent 256 stripes in a first-in/first-out continuously flowing range image. The vision system then can acquire a
photograph of this image from the buffer in one frame time (1/30 sec). Hardware for the encoding process is outlined in Fig. 5. Each horizontal line of the camera's image is scanned, and a counter, which starts at the beginning of each line, is stopped when the laser stripe is located. The value of the counter, which represents the range measurement or height for that particular line, is stored in a buffer.

Sixty new columns of range data (60 separate camera images) can be generated in 1 sec; a completely new 256 × 256 buffered range image can be gathered in 4.267 sec. The movement of the carousel is used to spread the range data over an entire scene. This performance is significantly faster than commercially available range imaging systems using similar principles. The stored range image is converted to analog form for transfer to a vision processor designed to accept data from a camera. The customized circuitry allows the acquisition and processing of a range image to occur in parallel.

Sparse Data Range Imaging Algorithm

The range image acquired from the special hardware is subsampled into both horizontal and vertical stripes. By using a sparse grid of range data, processing time is greatly reduced over the time necessary to process full range data. The number of stripes used is calculated to give a sampling density of at least one stripe every 1.5 in. both across and along the carousel. Height (gray-scale) discontinuities in the stripes are used to define the end points of contiguous stripe segments. These segments are stored in a data structure that records the x, y, and z coordinates of their end points.

A connectivity analysis performed on the stripe segments generates a list of potentially accessible mailpieces. Another data structure contains pertinent data on each piece. The height of each stripe segment end point within a piece is compared with the height of the end point of the contiguous and collinear segment in a neighboring parcel to determine which piece is on top of which segment. Then a graph is generated to represent the on-top-of relationship among all pieces in the scene. The nodes of the graph represent the parcels; the edges of the graph connect overlapping pieces with arrows pointing from the top piece to the bottom piece. An example of this type of graph is shown in Fig. 6. Any node without edges pointing to it (i.e., with an indegree of 0) represents an accessible irregular mailpiece. The centroids of all pieces above a minimum size are calculated and sent to the robot together with the graphical information.

The singulation algorithm, in conjunction with the described hardware, can accurately locate mailpieces 0.125 in. thick or more. A curvature criterion is applied to each piece to determine if it is cylindrical. All cylindrical pieces should be placed in a separate output stream, because downstream processes, such as address label imaging, can be performed by special equipment that can spin tubes.

The process is repeated for succeeding image scenes, at 4.267 sec intervals. Thus, all parts of the carousel are processed exactly once during each revolution of the carousel. Special processing handles parcels whose range images fall partly into two successive scenes to ensure that they are processed only once. This processing also handles very long parcels, which might fall into many successive range image scenes. Running on a 68000-based machine with an 8-MHz clock, the entire vision processing routine takes about 1.6 sec/image, typically finding three or four accessible pieces in a scene during that time. This is only a fraction of the 4.267 sec allotted for processing a scene.

Robot Target Selection Algorithm

The singulation algorithm runs under VAL II control in the AdeptOne robot controller. The routine is a loop that updates its choice of the best piece to be targeted for removal from the carousel every 78 msec, on average. This algorithm receives irregular-parcel centroid coordinates and graph information from the vision system, places them in a data structure (or list) of mailpieces on the carousel, and increments pointers to the first and last pieces on the disk. The first piece on the list is the next one to leave the robot's work area; the last piece is the one whose coordinates were the last received from the vision system. In Fig. 7, for example, "first" is h + 3; "last" is h + 7. If no new coordinates are received from the vision system, the routine reprocesses the pieces that remain on the carousel.
For each accessible piece in the list, the Adept controller determines which ones will be in the robot's work area at an increment of time in the future, and which of these pieces is the best to target for removal. The increment of time is based on the average area the robot reaches the piece. The robot's work area is the shaded area in Fig. 8. The area is small to limit the number of pieces processed through the selection routine in a typical pass, and to limit the length of possible robot moves. The position of a piece on the carousel is the basis for selecting the best accessible piece: the piece closest to a predefined point near the junction of the carousel and the take-away conveyor is always selected.

The coordinates of the piece chosen as the best possible target are placed in a special buffer. When this routine requests these coordinates, the graph representation of the heap is modified. The node representing the chosen piece is removed from the graph together with all edges leading from it. In this way, more parcels become accessible. In Fig. 6, for example, if piece b were removed, piece c would become accessible; if piece f were removed, piece h would become accessible, but piece e would remain inaccessible because it is under piece d. This graph modification will also prevent the robot from attempting to pick up a piece it has already delivered.

Obviously, if the robot requests new coordinates every 1.5 sec, and a new best piece is chosen every 78 msec, the same piece can be targeted for removal in successive 78-msec cycles, but never after it has been requested by the motion control routine. In fact, some pieces that are chosen as "best" are not picked up because the robot is removing a previously chosen piece at the time.

Eventually, with continuing revolutions of the carousel, every piece will be removed.

For the robot to pick up the targeted piece at its centroid, a time-dependent transformation from the vision system coordinate frame to the robot coordinate frame must be performed. Many robot systems provide such transformations for linear conveyors. For the disk configuration, however, no tracking command is available in the Adept, therefore, an approximation was written in VAL II. This transformation uses the conveyor-belt tracking encoder provided with the Adept. This encoder is mounted on the underside of the carousel and increments continuously as the disk rotates. Encoder values then can be used to obtain the current position of the carousel and all the pieces on it, and to calculate the rotational speed of the carousel. The two coordinate frames are depicted in Fig. 8. The current position of any mailpiece can be calculated exactly from the speed and geometry of the carousel, the angular offset of the two X axes, the encoder value at image acquisition, and the current encoder value.

To send the robot to the correct centroid of a chosen mailpiece, the future position of the centroid must be predicted, based on the distance it will travel in the time it will take the robot to make the desired move. Since travel time depends on the parcel's exact position on the carousel when it is to be picked up, an iterative solution involving a three-dimensional lookup table of travel times versus the x, y, and z positions of the centroid is used. To create the table, the workspace was partitioned into 1-in. cubes, and a program was written to move the robot from a drop point to each cube in a systematic manner. The travel time to each point was measured by the program and stored in the table.

When the motion control routine selects a targeted piece, it consults the lookup table to find how long the robot will take to reach the parcel's current centroid. Then, the robot's position is updated in terms of the distance the piece will move in that time. The table is consulted again, this time to see how long it will take the robot to reach this new point, and the position is recalculated, based on the new time. If a large discrepancy exists between the two predicted times, the cycle is repeated until two consecutive positions are within an inch of each other. This takes only one to three iterations at current carousel speeds. Centroid calculations are usually accurate to within the tolerance of the end-effector; however, a poor range image, due to dropouts, errors, and occlusion effects, may cause the calculated centroid to be off considerably.

Fig. 7. Indexing of accessible pieces on the carousel.

Fig. 8. Location of the vision and robot coordinate frames and the robot work area on the carousel.
Adaptive Vacuum Gripper

The end-effector developed for this system is a simple, lightweight mechanical device, inexpensive to manufacture and maintain. The end-effector is depicted in Figs. 9 and 10. The four symmetrically placed vacuum cups provide sufficient lifting capacity for the irregular parcels and pieces that fall within the size limitations of the system. The cups are individually controlled by electrically driven stationary air solenoid valves. For small mailpieces, only one or two cups need be activated, as directed by the vision system. The entire gripper assembly weighs only 1 lb.

RCA also developed the control device for the vacuum cups. The design is based on a configuration originated by SRI International (Fig. 11). When the control air pressure is shut off, the spring pushes the piston up and opens the ports, allowing vacuum flow through the lifting cups into a surrounding plenum. When the control air pressure is turned on, the vacuum is shut off by forcing the piston down, thus covering the ports. The control air then leaks into the cups, providing positive pressure and preventing adhesion to an unused cup. The outer shell of the gripper also serves as the outside of the vacuum supply plenum. The piston valves are located in this plenum. A 4-hp Rotron regenerative blower supplies the vacuum to the gripper. Its pumping capacity assures that useful suction lift is maintained even if leaks occur between the vacuum cups and the mailpieces. In practice, the bellows-type vacuum cups being used provide an effective seal for a wide variety of mailpieces.

Conclusion

The irregular-parcel and -piece singulation system described here performs at high speed and high efficiency with a wide variety of objects. The system is basically simple, using state-of-the-art, largely off-the-shelf technology. Plans to enhance the system include improved vertical resolution of the range imager to facilitate the handling of smaller and thinner mailpieces and refinements in the robot path-planning algorithms to improve speed.

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References


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