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Development of a Mechatronic Sorting System for Removing Contaminants From Wool

Liwei Zhang, Abbas Dehghani, Zhenwei Su, Tim King, *Senior Member, IEEE*, Barry Greenwood, and Martin Levesley

***Abstract*—Automated visual inspection (AVI) systems have been extended to many fields, such as agriculture and the food, plastic and textile industries. Generally, most visual systems only inspect product defects, and then analyze and grade them due to the lack of any sorting function. This main reason rests with the difficulty of using the image data in real time. However, it is increasingly important to either sort good products from bad or grade products into separate groups using AVI systems. This article describes the development of a mechatronic sorting system and its integration with a vision system for automatically removing contaminants from wool in real time. The integration is implemented by a personal computer, which continuously processes live images under the Windows 2000 operating system. The developed real-time sorting approach is also applicable to many other AVI systems.**

***Index Terms*—Automated visual inspection (AVI), color image, contaminants, mechatronic sorting system, wool.**

I. Introduction

CONTAMINANTS of different colors, sizes, and shapes are always present in raw wool used for textile manufacture. These contaminants mainly include polypropylene (PP) baler twines, packaging materials, plastic materials, urine/fecal-stained wool, paint sheep marker, and black pigmented fibers, and their sizes are generally 4–20 cm long. For many practical applications, their presence will lead to serious color defects in products such as woven fabrics, carpets, and knitwear, where a solid color is required because they do not dye to the same shade as wool fibers. Currently, in the United Kingdom alone, this problem is conservatively estimated to cost the textile industry more than £6M each year.

In more recent years, the automatic removal of contaminants from raw wool has remained a challenging problem. Currently, they are only manually removed during the wool scouring (cleaning and degreasing) process by human visual inspection. However, the efficiency of the contaminant detection and removal by the pickers, often working for long hours at this tedious task, is very low; moreover, significant amounts of unseen and unwanted materials still remain in the wool after picking [1].

This study develops an AVI system to automatically detect and remove contaminants from wool to increase the efficiency of contaminant removal and avoid the drawbacks of inspection by human operators. The requirements of the developed system are that it should

- be able to identify all types of contaminants (minimum size is roughly 4 cm);
- be able to sufficiently reduce contaminant levels to allow uniform dyed solid shades to be achieved;
- remain stable and operate in real time;
- be easy to incorporate into wool scouring lines (typically running at 5 m/min);
- satisfy the requirement for a production rate of at least 1000 kg/h.

II. Background

In visual servo control of robotic manipulators, it is quite common to use visual data to control the action of these robots [2], [3] where open-loop or closed-loop controllers were designed and used. Although applications of processing images for automatic control in noncontact inspection have been explored and investigated [4]–[6], fully automatic control using the imaging data has yet not been successful.

In AVI systems used for process control in the textile industry, there exists one case of implementing closed-loop control using visual sensing data [7], where a knowledge-based process control system incorporating a machine vision system was used. However, the control process could not satisfy the production rate requirement. Although AVI systems for inspecting foreign or defective materials are widely used in many fields, only a few can successfully complete online real-time control using continuous incoming image data. A computer vision-based system for automatic lace scalloping has been reported by Shih *et al.* [8], but details of the control process were not presented.

Earlier research work on contaminant removal from wool and other fibers comes from CSIRO Division of Wool Technology, Australia [9]. In their system, optical inspection was tried but hampered by the need to separate the flow of scoured wool into six separate streams. As a result, the efficiency and performance of the sorting were not promising in their system. Later, Langenhove *et al.* [10] developed a quality control machine to detect and remove contaminants from raw cotton at a throughput rate of up to 1500 kg/h. The need for contaminant removal from cotton [11] resulted in the further development of an AVI system

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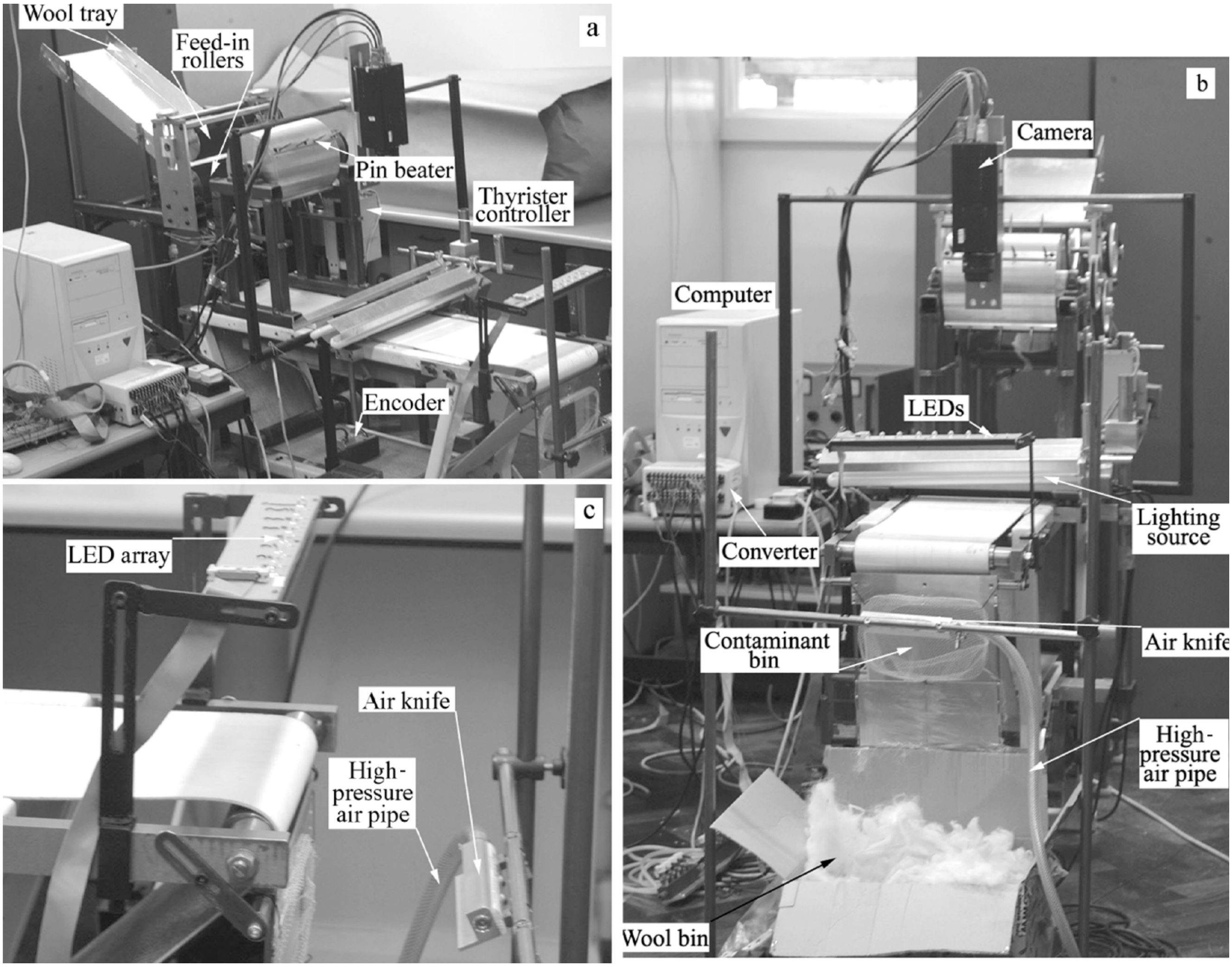

Fig. 1. Test rig of automated visual inspection system in the lab.

to inspect foreign fibers and blow them off using high-pressure compressed air, which was located at a point immediately before carding.

However, these systems can only detect and remove contaminants depending on color difference. Furthermore, they could not be used for contaminant removal from wool because wool fibers are much longer than cotton and more mingled.

In the two systems [10], [11] described previously, the rejection device was installed near the point of inspection. This means the control components must work within a short fixed period of the image being processed. As a result, this system is not flexible enough to deal with the variable speed of image processing.

Despite an extensive literature search, no literature was found to report the successful integration of a sorting function with a machine vision system. The sorting system presented in this article can be installed far away from the inspection location. Moreover, the method by which the continuous incoming live images data are used for real-time control is general and applicable to many other AVI systems.

The AVI system developed in this article consists of three subsystems: wool preopening system, vision system, and sorting system. The wool preopening system [Fig. 1(a)] is described in Section III. The vision system [Fig. 1(b)] is discussed in Section IV. Finally, the development of the sorting system [Fig. 1(c)] is reported in Section V. System performance tests are carried out in Section VI, and conclusions are drawn in Section VII.

III. Preopening System

In current wool scouring plant, the presentation of scoured wool is not suitable for automatic contaminant detection and removal because the wool tufts are entangled together in a thick layer (about 20–30 cm), running at a speed of 5 m/min. To present the wool in a uniform thin layer for inspection, first, the conveyor in the inspection zone was run at a speed of 20 m/min so the wool could be drafted into one-fourth of the original thickness. Second, an opening device has been designed and constructed to separate wool into small tufts, and distribute it into a loose and thin layer so all the contaminants are visible on the surface of the wool and can, therefore, be easily identified and blown away.

An attempt was made to simulate the industrial equipment [12]; in the present experimental test rig, an opening system was

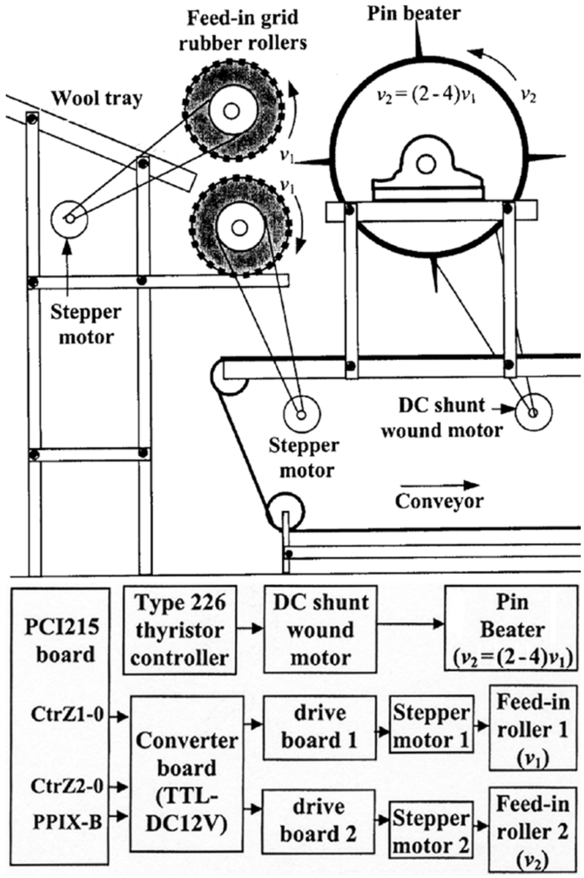

Fig. 2. Schematic diagrams for the preopening system.

constructed to separate the wool into small tufts without further subdividing the contaminants [Fig. 1(a)]. The device consisted of two rubber-covered, feed-in rollers and one large roller with four groups of pin bars. The feed-in rollers gently restrain the wool tufts and are driven by two independent stepper motors. An Amplicon PCI215 counter/timer board sets both stepper motors' speeds as the drive speed of the conveyor. The large roller with pinned bars is used to open out the wool tufts from the feed system. A dc shunt wound motor drives the large roller running between two to four times faster than the feed-in rollers. The schematic diagrams for the preopening system are shown in Fig. 2.

The experimental results obtained from the laboratory preopening system were successfully used to modify the hopper machine [12] for wool preopening in a large-scale factory test rig.

IV. Vision System

A. System Configuration

Fig. 1 shows the constructed online AVI system. The main components of the vision system are a Dalsa Trillium 34-color line scan camera (resolution 2048 pixels, maximum line scan rate 11 kHz), a host computer (3.06 GHz Pentium IV CPU, 1 Gb RAM), a Coreco Viper-Digital framegrabber installed in the host computer, two fluorescent tubes with high-frequency electronic ballasts, and a 235-mm wide conveyor running at 20 m/min. The wool on the conveyor runs under a glass pressure plate in the inspection zone, which compresses it to reduce shadows on the surface.

B. Online Image Acquisition and Processing

Development of real-time software has been undertaken using the Coreco Sapera imaging library package and Microsoft Visual C++ 6.0. The whole image acquisition process is controlled by the i960 system controller and the PLX chip (a PCI interface chip targeted at video applications) on the Coreco Viper-Digital framegrabber. The host CPU is not involved with the management of data transfers, address generation, and interrupt of every image [13]. As a result, live image acquisition and processing are a continuous procedure, where the host computer displays and processes the images buffer by buffer, in parallel with the image acquisition.

Real-time image-processing algorithms were developed in RGB and HSV color spaces. First, every color image in the RGB color space is split into red, green, and blue gray-scale images and transformed into the HSV color space. Then, every gray-scale image in the RGB color space is separately processed by global and local adaptive threshold algorithms for identification of deep color, light, and white color contaminants; the saturation gray-scale image in the HSV color space is processed by a global adaptive threshold algorithm for identification of white, light yellow, and brown color contaminants. The last processed image is the addition of the processed gray-scale images. Finally, the blob features were extracted, and the coordinates of the centroids of the identified contaminants were calculated. The algorithms are capable of identifying 96% of all typical contaminant types (50), including all the deep color contaminants and most of the light and white color contaminants with minimum size of 4 cm long, both in the lab. and in the factory test rig. A typical processed image is shown in Fig. 3, where the small white PP (4 cm long, 3–4 mm in diameter) and light blue PP (3–4 mm in diameter) were clearly identified. More details of the image-processing algorithms are presented in [14] and [15].

In the following development, the camera runs at about 2000 lines/s, and only the global adaptive threshold algorithm is used to simulate practical factory situation due to the short distance (0.53 m) between the camera and the end of the conveyor (DCC) in the lab. test rig (compared with 1.2 m in the factory). The time range of processing one buffer of image (1024×2048) is 120–150 ms. If the DCC were longer, complex image-processing algorithms could be used for the development of the sorting system.

V. Development and Integration of a Mechatronic Sorting System

For the development of the sorting system, a mechanism is needed that is capable of rapid response to the continuously incoming data from the image processing and that has enough energy to efficiently remove the contaminants once identified. Besides these requirements, when and how the removal mechanism should be actuated must be solved for completing the real-time contaminant removal. To achieve this, the sorting system needs to be integrated with the vision system.

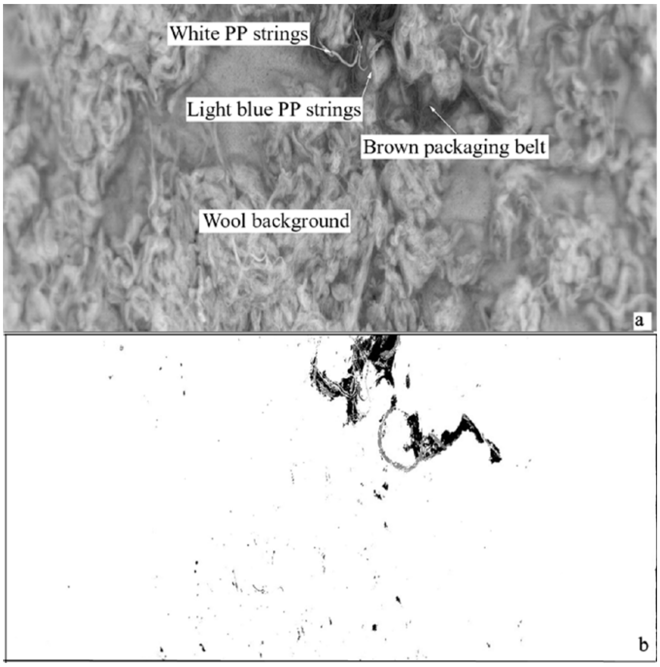

Fig. 3. Typical wool image with contaminants and processed image. (a) Original image. (b) Processed image.

The main principle of the integration of the sorting system is to change the processed high-resolution image (resolution 1024×2048) to a low-resolution one, synchronized with the spatial position of the moving contaminants on the conveyor. The spatial positions can be obtained by extracting the coordinates of the contaminant centroids from the processed live images. The low-resolution image data are then stored in a circular buffer. The data in the circular buffer are sent to a removal mechanism one by one to remove the contaminants using a synchronous interrupt routine. The time at which the solenoid valves are actuated can be calculated to efficiently remove the contaminants without extensive loss of wool.

The choice of removal mechanism, generation of the circular buffer, the synchronous interrupt controlled data transmission mode, and the integration procedure are presented in the following sections.

A. Choice of Removal Mechanism

Two possible methods were considered to remove the contaminants, namely, mechanical and pneumatic removal methods.

For the mechanical removal method, a robotic device was considered. A pneumatic actuator or a solenoid can be used to drive a mechanical gripper to remove the contaminants within a short time interval (about 512 ms in this application). However, it is difficult to complete the necessary actions within such a short time interval. Moreover, the wool and contaminants are very light and difficult to release after they are gripped. Therefore, the robotic device was ruled out.

For the pneumatic removal method, air knives are used instead of air nozzles because the active length of the air knives is much longer than the air nozzles. Initially, an air knife using a high-velocity air source (from blower, type ATV28*U41N4) was considered to be a potential mechanism. However, it was frustrated due to the lack of readily available product to control the high-velocity air flow through the air knife. As a result, the attention moved to the use of high-pressure compressed air. This allows the use of smaller diameter pipes. In consequence, the solenoid valves with short response time (less than 20 ms) can be used to control the air flow through the air knife. The length of the air knife can be selected to suit practical end use.

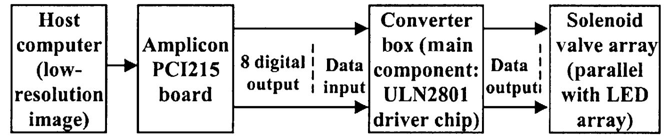

Fig. 4. Schematic structure of the control system.

For the laboratory test rig [Fig. 1(b)], only one air knife (15 cm long) was used. For the large-scale factory trials, however, an array of air knives (8) would be installed across the 1.45- m wide conveyor. To simulate control in this situation, eight less powerful solenoid valves (24 V dc) were installed at the end of the conveyor, which directed jets of the high-pressure compressed air through the nozzles. These valves are controlled by the Amplicon PCI215 board. One converter is used to change the TTL-level signals to 24 V dc signals. The schematic structure of the control system is shown in Fig. 4. Eight light-emitting diodes (LEDs) were connected in parallel with the eight solenoid valves to indicate the status of the valves.

B. Generation of a Circular Buffer

By the time the first buffer of image data has been processed and moved to the solenoid valve array, two further buffers of image data have been acquired and processed into low-resolution image data on the lab. test rig. To not lose the low-resolution image data, a buffer space is needed to store them. A printer buffer [16] was successfully modified into a circular buffer for this purpose. Every buffer of the high-resolution image (1024×2048) is changed to 1 byte of a low-resolution image once it has been processed. The size of the low-resolution image is chosen according to the required actuating time of the solenoid valves for efficiently removing the contaminants. The minimum size of the buffer is limited by the distance between the camera and the solenoid valves, whereas the maximum size of the buffer is limited only by the size of the computer free memory.

Based on the lab. test rig, the minimum buffer size is 3 bytes. In the integration program, a circular buffer with 200 bytes is created to store the low-resolution image data (Fig. 5). It uses two address pointers: one for data input to the circular buffer, and the other for data output to the solenoid valve array. Input and output address pointers are initially set to the beginning address of the buffer. As soon as one buffer of the live image is processed and transformed to a low-resolution image, the low-resolution image data are sequentially input to the buffer. Both the input address pointer and the output address pointer progress down, and the addresses are increasing down. After the data are input to the last address in the buffer, the input address pointer is reset to the beginning address of the buffer, and the input process

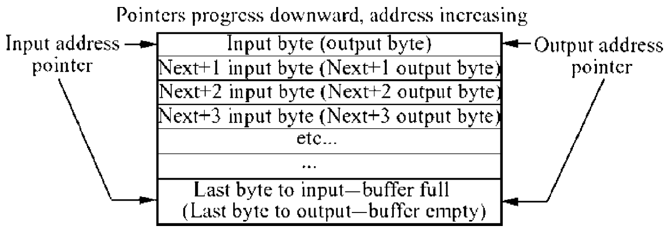

Fig. 5. Schematic diagram of the circular buffer.

continues. The data output from the circular buffer is controlled by a synchronous interrupt routine. When the byte in the last address of the buffer is sent to the solenoid valve array, the output address pointer is reset to the beginning address of the buffer, and the process of data output continues.

C. Interrupt Controlled Data Transmission

An interrupt is an event that forces the CPU to modify the sequence of actions. In this application, a hardware INTR (interrupt request) [17] is used because the Amplicon PCI215 board can generate an INTR signal. Normally, a real-time system interacts with external events via the computer hardware. External events are converted into interrupts and handled by a device driver. In the Windows 2000 operating system, the interrupt is processed in two stages. First, it is processed by a short interrupt servicing routine (ISR). Afterward, the process is completed by executing a deferred procedure call (DPC) [18].

To complete real-time operation of the AVI system in this application, an interrupt-controlled data transmission mode is used for passing the low-resolution image data to the solenoid valves. The Amplicon PCI215 board has six external interrupt sources [19], two of which (outputs of the counters CtrZ1-1 and CtrZ2-1) are used to generate INTR signals to the host computer. Every counter on the Amplicon PCI215 board has six working modes, two of which (mode 0-Interrupt on terminal count and mode 1-Rate generator) are used to configure the counters CtrZ1-1 and CtrZ2-1 for generation of the INTR signals. These interrupts are then handled by Windows callback functions (WCFs) to complete data output to the solenoid valve array. In this way, the CPU and the counters of the Amplicon PCI215 board can work in parallel, which satisfies the requirement of real-time control.

D. Generation of Synchronized Signals

For the sorting system to work reliably, it is essential that the interrupt-controlled data transmission is synchronized with the movement of the wool on the conveyor. To achieve this, an encoder (resolution 12 pulses/mm), driven by the belt, is used to provide A and B RS422 differential signals. These signals are used for two key tasks: 1) to ensure the first data in the circular buffer is sent out to actuate the solenoid valves at the right time; and 2) to control the line scan rate of the camera and generate a fixed integration time. The A and B signals from the encoder are fed to the Coreco Viper-Digital framegrabber to build up the EXSYNC signal (Fig. 6). It is the signal that is used to trigger the camera to read one line image. In this way, the line scan rate is synchronized with the conveyor speed. As a result, small variations on the belt speed are taken into account.

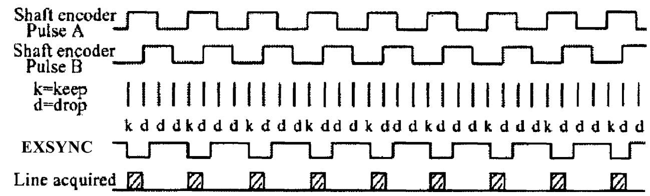

Fig. 6. Timing diagram of line scan with encoder.

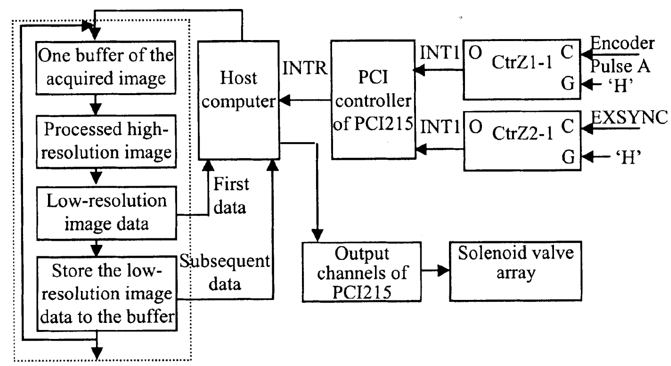

Fig. 7. Flowchart of integration of the sorting system.

Based on the previous analysis, the encoder signals and EXSYNC signals are used as synchronous signals for the interrupt-controlled data transmission. The first data in the circular buffer should be sent to the solenoid valve array after a fixed number of pulses (depending on DCC) from either A or B signal have been counted following the image acquisition. The subsequent data in the circular buffer should be sent each time when every 1024 EXSYNC pulse has been counted.

E. Integration Procedure of Sorting System

The flowchart of integration of the sorting system is shown in Fig. 7. The process of integration is separated into two parts. First, the low-resolution image (1×8) data transformed from the processed high-resolution images with the spatial position of moving contaminants on the conveyor are sequentially stored in the circular buffer. Second, data in the circular buffer are sent to the solenoid valve array under the control of the spatial synchronization through the interrupt routine of the host computer. Following the movement of the conveyor, the output of the counter CtrZ1-1 [the encoder signal as its clock source, mode 0, counting number 6360 $(530\ \mathrm{mm} * 12\ \mathrm{pulses/mm})$] is used to generate the first INTR signal. A WCF handles the INTR signal and sends the first data in the circular buffer to the solenoid valve array; the output of the counter CtrZ2-1 [EXSYNC signal as its clock source, mode 2, counting number 1024 (width of high-resolution image)] is used to generate the subsequent INTR signals. A WCF is periodically called to handle the INTR signal and sends the subsequent data in the circular buffer to the solenoid valve array. The schematic diagram of the interrupt occurrence is shown in Fig. 8. The two WCFs are presented in the Appendix.

The data in the circular buffer are updated in parallel with the image acquisition and image processing. To keep the data input process synchronizing with the data output process, the output address pointer is checked in the second WCF. If the output address pointer equals the input address pointer, the WCF

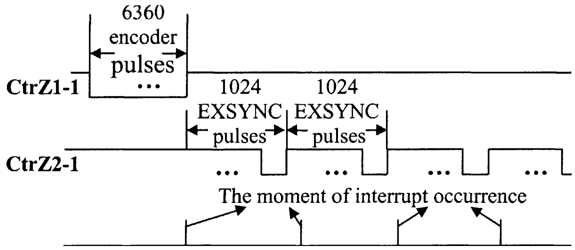

Fig. 8. Schematic diagram of interrupt occurrence.

TABLE I
EXPERIMENTAL RESULTS

Contaminant types and trials		Deep color	Light color	Mixed color
First trial	Total	8	13	15
	Removed	8	12	13
	Success rate (%)	100	92.3	86.7
Second trial	Total	8	13	15
	Removed	6	11	12
	Success rate (%)	75	84.6	80

is jumped out and is then rapidly called again until the output address pointer does not equal the input address pointer.

VI. Performance Test and Analysis

A wide range of tests were carried out to evaluate the performance of the developed AVI system. These cover two aspects—contaminant identification tests (results were reported in Section IV-B), and accuracy and stability tests for the sorting system, discussed in the following sections.

A. Accuracy and Stability Tests on Lab. Test Rig

The accuracy and stability tests on the lab. test rig (Fig. 1) include signal accuracy test, accuracy test for practical sorting, and signal stability test.

The signal accuracy test is used to verify whether the corresponding solenoid valves can be actuated at the right time when the contaminants pass through them. An LED array is used to inspect the accuracy of the output signal to the solenoid valve array. For easy and repeatable testing, wool and several contaminants were uniformly stuck on the surface of the conveyor (using double-sided adhesive tape). The vision system and integration program were then run. It was found that the corresponding LEDs could correctly illuminate the contaminants at every occasion when the contaminants passed under them.

An accuracy test for practical sorting was carried out using one air knife and one solenoid valve. Loose wool with contaminants was fed onto the conveyor through the preopening system. The vision system and the integration program were then run. It was found that the contaminants were blown into the contaminant bin at every occasion as the contaminants pass through the air knife. The actuation time of the solenoid valve is about 512 ms, which is enough to remove the contaminants without unnecessary loss of wool.

Signal stability test was undertaken to check the reliability of the sorting system. The setup for the test is the same as for the signal accuracy test. The test, which was carried out numerous times, involved running the system continuously for about 3 h. When the system was running, the contaminants could also be dropped into the inspection zone to check the accuracy of the output signals to the solenoid valve array, as indicated by the corresponding LEDs. The test has proved that the system could remain stable and accurate after being run for a long period of time.

B. Accuracy Test on the Factory Test Rig

A factory test rig was constructed on the basis of the techniques developed on the lab test rig. The modified hopper machine was used to open and distribute the short to medium entangled wool into a uniform thin layer to the inspection zone. The conveyor in the inspection zone runs at 20 m/min, and the same vision components as those on the lab. test rig were used to inspect the wool on the whole width of the conveyor (1.45-m wide). An array of 15-cm long air knives (8) driven by the solenoid valves (Norgren VM10) were installed at the end of the conveyor. The DCC is 1.2 m compared with 0.53 m for the lab. test rig.

In this test, the real-time image-processing algorithm presented in Section IV-B was used, for which the time range for processing one buffer of image is 650–950 ms. The camera line scan rate of 800 lines/s and low-resolution image size of 2×8 bytes were set for real-time AVI.

Two trials were carried out for the accuracy test. The first trial was to drop different types and shapes of contaminants (minimum size 4 cm) onto the conveyor, upstream of the inspection point. The second trial was carried out by mixing different types of contaminants with wool in the hopper tank (other test conditions were the same as for the first trial). In both trials, the success or failure of contaminant removal was observed by human vision. Every trial was repeated three times. The results are summarized in Table I, where light color contaminants include white color ones and mixed color contaminants include deep color and light color ones.

In trial 1, a high success rate of contaminant removal is obtained because the contaminants were all present on the surface of the wool. Unremoved contaminants were all light in color and were not identified. In trial 2, a comparative lower success rate of contaminant removal was obtained because some unremoved contaminants were covered by wool and thus not identified, despite the wool having been presented in a very thin layer.

C. Results and Analysis

Because the conveyor on both the lab. test rig and factory test rig runs four times faster than the speed of the conveyor in the scouring line (5 m/min), when the AVI system fits into the scouring line, the system will be able to maintain its existing production rate. Only a small amount of wool was blown away along with the contaminants.

Two factors have been considered to affect the accuracy and stability of the sorting system. One is the rising edge of the EXSYNC signal. The other is the Windows 2000 operating system.

The rising edge of the EXSYNC signal (Slope) makes the generation of the INTR signal earlier than the expected time interval.

The Windows 2000 operating system (based on Windows NT technology) is not always suitable as a real-time operating system [20]. It takes time for the CPU to deal with the INTR signal from the sorting system. In addition, the WCF, which is scheduled through the operating system, sometimes executes after the interrupt occurs. However, the delays not only are small, but can also compensate the error caused by the rising edge of the EXSYNC signal. Moreover, they are not accumulated due to the automatic counting of the counter (Fig. 8). Therefore, the AVI system can remain stable and accurate for a long period of time.

In addition, the maximum DCC is limited by the maximum counting number of the counter. If 32 bits of counter and a lower resolution encoder were used, the DCC could be very long due to the use of the circular buffer.

VII. Conclusion

This paper describes the development and integration of a sorting system with a vision system. The developed image processing algorithms identify all the deep color contaminants and most of the white and light color contaminants. The presented synchronous interrupt data transmission mode based on the Windows 2000 operating system can successfully complete the sorting task. This method is also applicable to other AVI applications, where a control task is required. Following the successful integration of the sorting system with the vision system in the factory test rig, it was confirmed that the corresponding solenoid valves were correctly actuated at every occasion. The contaminants were efficiently removed in real time by the corresponding air knife/knives under such a conveyor speed of about 20 m/min and the camera line scan rate about 800 lines/s. This indicates that a faster PC with Windows 2000 or Windows NT operating system could easily complete both image acquisition, processing, and sorting tasks in parallel. It has also been shown that as a result of using a circular buffer, the actuators (the solenoid valve array in the application) can be located remotely from the camera, which greatly increases the range of applications in which this type of system will be needed.

Appendix

```
void CALLBACK ProcessInterrupt (short h,
WPARAM wParam, ULONG lParam)
{ //Send the first data in the circular
buffer
DIOsetDataEx (hboard, PPIX, 0,
*bufferout);
 *bufferout = 0;
 > > >TCsetGate (hboard, Z2, 1, GAT_VCC);
 > > >TCsetMode (hboard, Z2, 1, 2);
 > > >TCsetCount (hboard, Z2, 1, 1024);
 > > >TCsetUserInterrupt(hboard,
ProcessInterruptz2, 0,0,0,0,0,0);
 > >bufferout++; }
```

```
void CALLBACK ProcessInterruptz2 (short h,
WPARAM wParam, ULONG lParam)
{ //Checking the buffer pointers
 > >if (bufferout == bufferin)
{ if (bufferout == (buffer + 200))
 > > > > > >bufferout = buffer;
 > > > >TCsetMode(hboard, Z2, 1, 0);
 > > > > > >TCsetCount(hboard,Z2,1,2);
 > > > > > > >m = 0;
 > > > > > > >return; }
//Sending subsequent data in the circular
buffer
 >DIOsetDataEx(hboard,PPIX, 0,
*bufferout);
 > > > > >*bufferout = 0;
 > > > > >bufferout++;
if (m == 0)
 > > > >{ TCsetCount(hboard, Z2,1,1024);
 > > > > > > > >m = 1; }
 >if (bufferout == 200)
 > > > > > > >bufferout = 0; }
```

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