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Automatic Page Turner Machine for High-speed Book Digitization

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Abstract— **In recent years, there has been an increasing demand to digitize a huge number of books. A promising new approach for meeting this demand, called Book Flipping Scanning, has been proposed. This is a new style of scanning in which all pages of a book are captured while a user continuously flips through the pages without stopping at each page. Although this new technology has had a tremendous impact in the field of book digitization, page turning is still done manually, which acts as a bottleneck in the development of high-speed book digitization. Against this background, this paper proposes a newly designed high-speed, high-precision book page turner machine. Our machine turns the pages in a contactless manner by utilizing the elastic force of the paper and an air blast. This design enables high-speed performance that is ten times faster than conventional approaches and, in addition, causes no obstruction in the digitization process. This paper reports the evaluation of the proposed machine using various types of paper with different qualities. Our machine achieved almost 100% success rate when turning pages at around 300 pages/min, showing that it is a promising technology for turning pages at high-speed and with high precision.**

I. INTRODUCTION

Portable information terminals such as tablet computers and smartphones have become widely used, and various services based on digital archiving and sharing of a vast amount of information are being developed. Along with this technology trend, media content, particularly in the form of books, is attracting increasing attention, and demands for book digitization have been growing rapidly worldwide. High-speed book digitization is an important technology that will have a strong impact in various fields, including document preservation, business tasks and everyday applications. However, there are no technologies that have sufficient ease-of-use and high-speed performance to meet the demands of potential users.

An important technology that has made significant progress under this situation, called *Book Flipping Scanning*, has been proposed [1]. This is a new style of scanning in which all pages of a book are captured while a user continuously flips through the pages without stopping at each page. Various systems embodying this concept have been proposed and demonstrated to meet the diverse requirements arising in different markets, including a basic proof-of-concept prototype [1], a high-speed multi-camera array system [2], and a mobile system using a single camera [3]. However, in these systems, page flipping is performed manually, which causes problems such as a low page-flipping speed and inaccurate page-flipping. In particular, multiple pages are frequently flipped simultaneously without being adequately separated, and the system fails to digitize the hidden pages. Also, this type of manual operation is not a realistic solution when numerous books need to be digitized. In this way, manual page flipping has limits in terms of speed, accuracy, and continuous operation. In order to surpass these limitations, an automatic page turner machine is required.

This paper describes a new book-page turner machine that meeting these three demands—high speed, accuracy, and automatic operation—in order to establish an innovative high-speed book digitization technology based on *Book Flipping Scanning*. This machine is capable of operating at high speed, exceeding the performance of conventional technologies. Also, in order to specialize the machine for book digitization, we adopt a new configuration that is completely different from conventional systems, in which no handling device is placed on the paper surface, so that the entire document image can be captured. Based on this design, we developed the test machine shown in Fig. 1. Experimental results show that our machine achieved high page flipping performance with good precision. We believe that this system is a promising technology whose adoption will spur progress in high-speed book digitization.

II. PAPER MANIPULATION TECHNOLOGY AND REQUIREMENTS FOR OUR PAGE TURNER MACHINE

A. Related technology

Conventionally, various manipulation mechanisms for handling paper have been proposed. However, most mechanisms have focused on unbound stacks of paper [4], [5], and not books.

On the other hand, there are a number of practical automatic book-page turner machines designed for flipping a musical score for a musician, or helping a patient to read a book [6], [7], [8]. The purpose of these types of systems is to support reading by a user, and so the speed is designed to be low. The basic configuration of these systems employs a roller structure, in which a roller is rotated in contact with the paper to turn the pages. This type of configuration has the drawback of occlusion, where the roller appears on the book and can be an obstacle that prevents the camera from performing efficient and high-speed digitization in one shot. Therefore, this configuration is not suitable for book digitization.

There are also some automatic page turner machines designed for book digitization, although the number of such systems is small. Examples include a configuration using a roller [9], a system in which sticks resembling fingers

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flip pages [10], and a system using a manipulator that has a paper-suction function [11], [12]. These systems employ components that are placed in contact with the pages to flip them, so that they have limited speed, typically about 20–50 pages/min.

B. Requirements for high-speed automatic page turner machine

The following three requirements are essential for achieving high-speed book digitization. As described in the previous section, the conventional technologies have not been able to meet all of these requirements.

High speed: *Book Flipping scanning* aims at a target speed of over 300 pages/min. This performance level is, in principle, expected to be achieved by employing a sensing technique that captures document images in three dimensions. In practice, however, this would require a greater than 10-times increase in performance, compared with present systems.

Accuracy: Essentially, book digitization requires capturing all pages. Therefore, unacceptable flipping includes the case where multiple pages are turned at the same time without being adequately separated, resulting in failure to capture obscured pages, and the case where the paper is highly deformed during flipping, which reduces the quality of the digitized document images.

Non-contact and occlusion-free operation: For book digitization, it is necessary to avoid a configuration where obstacles hide part of the book in the viewing field of the camera that captures document images. Therefore, the space between the book and the camera must be free of any occluding object. In addition, the page-turning must be realized with a non-contact mechanism.

These requirements demand a mechanism that drastically differs from the conventional approaches.

III. High-speed automatic page turner machine

A. Basic principle

Our proposed machine turns pages one-by-one in a non-contact manner by using the elasticity of the paper itself to recover its shape from a curved state, assisted by a blast of air.

This machine manipulates a planar surface formed by the edges of the pages at the opposite side from the spine when the book is curved. We call this part the edge face in this paper. As shown in Fig. 2, at this edge face, we confirmed that the pages are overlapped and aligned at regular intervals, and their ends are approximately parallel in a local region. Therefore, by moving a manipulator perpendicular to the ends of the pages while maintaining the edge face shape, when each page is set free, it can rise due to an elastic force caused by the curvature. By blowing air into the space formed between the rising page and the next page below it, the paper will be turned to the opposite side.

The action captured at high speed when the pages are turned is shown as a sequence of images in Fig. 3. When a page is set free from the manipulator, it is released and floats above the next page below it. The air blown into the space between the target page and the next page causes the page to turn, as expected. This design is basically based on a similar approach to that used by a human reader. However, the manual operation has low accuracy because the human finger motion has low resolution, a blast of air is not used, and the deformation of the flipped pages is large. Our system is designed to achieve high-precision, high-speed page turning by effective mechanization based on this design concept.

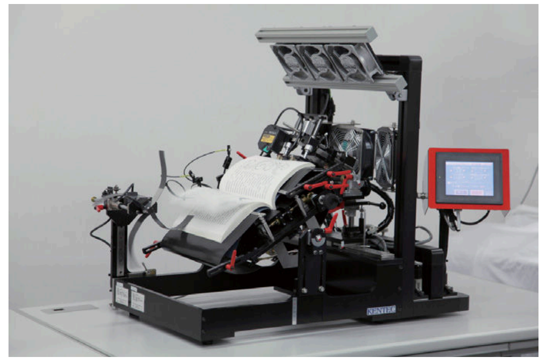


Fig. 1. Automatic page turner machine.

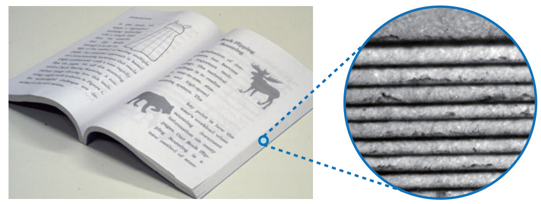


Fig. 2. Enlarged view of the side surface (edge face) of a book.

Fig. 4 illustrates the motion of the manipulator. As shown in this figure, the operation of this machine consists of three steps.

1) The manipulator is moved perpendicular to the ends of the pages while maintaining the edge face shape.
2) The top page is set free.
3) The released page is turned to the opposite side.

In repeating these three steps, the second step for the next page should not begin until the third step is completed for the previous page. At least, the flipped page needs to be out of the field of view of the camera in order to capture the next page before the manipulator reaches the next page. In this paper, we assume that turning of the next page needs to start after the previous page reaches the stack of paper on the opposite side. If we can design the machine under this condition, in principle, the pages can be digitized one-by-one during their turning motion without missing any pages. Therefore, when the time taken to complete the task of flipping each page, which is the period elapsed between the page being released from the manipulator and being stacked on the opposite side, is t [s], the movement speed of the manipulator v [μm/s] needs to meet the following condition:

$$t < \frac{l}{v} \tag{1}$$

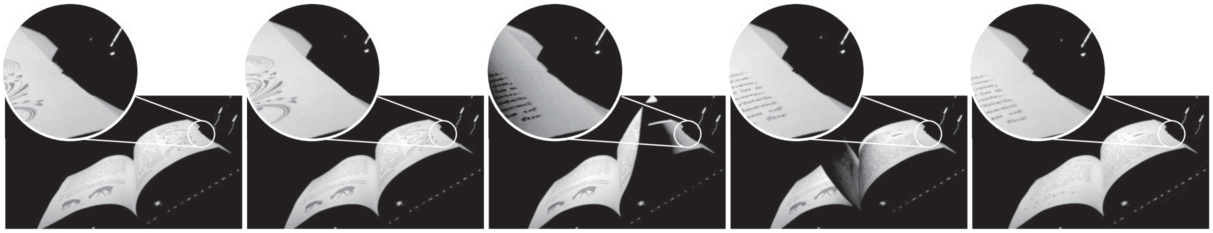


Fig. 3. Slow motion image sequence showing the page turning in our system. We can see that the top page is free after the released page is turned to the opposite side.

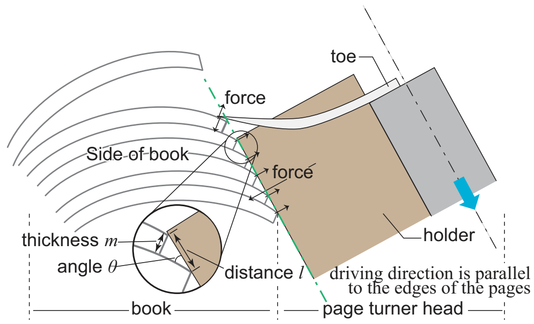


Fig. 4. Motion of the turner head.

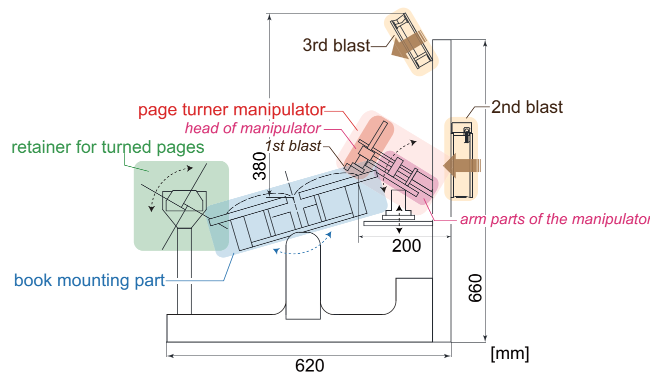


Fig. 5. Configuration of the designed high-speed page turner.

Here, l is a distance shown in Fig. 4.

Also the target speed P [pages/min] needs to meet the following condition:

$$\frac{lP}{v} < 60 \tag{2}$$

From equations (1) and (2), the condition for the speed v is

$$\frac{lP}{60} < v < \frac{l}{t} \tag{3}$$

In a preliminary experiment using a high-speed camera, we confirmed that the time t was around from 140 ms. For example, when a book consists of sheets of paper whose thickness m is 100 μm and the angle between the edge face and the page surface θ is 30 degree, the distance l shown in Fig. 4 is 200 μm. Therefore, in order to achieve the target speed of $P = 300$ pages/min, the manipulator speed should be set to 1,000–1,400 μm/s.

B. Configuration of the machine

Fig. 5 shows the configuration of our proposed high-speed automatic page turner machine. The machine consists of four parts: a book mounting part, a page turner, blowers, and a retainer for holding the turned pages. This configuration meets the requirements described in Section II-B for non-contact handling, high-speed flipping, and no occlusion in the page imaging region.

The size of the books that can be handled with this system is from A6 to A4, the maximum book thickness is 50 mm, the basis weight of the paper is 50–150 g/m^2, and the page thickness is 50–150 μm. Also, the sizes of pages in the book must be uniform, and the edge face used for manipulation should be planar when the book is set in the machine. In this design, the manipulator for page flipping is mounted at the right-hand side of the book, and each page is turned from this side to the left-hand side.

The details of each part are described in the following subsections.

C. Book mounting part

The book is placed on the book mounting part, and the spine is clamped from both sides. The configuration of book clamp is shown in Fig. 6. As shown in this figure, by rotating the 1st axis, the 2nd axes are rotated. Based on this mechanism, the clamp is driven axisymmetrically to the center of this part. After the book is clamped, the book is slanted in order to ease turning of the pages to the left-hand side under their own weight. In this design, the inclination angle is variable from the 0 to 45 degree.

Next, all pages are set on the right-hand side and are curved to generate elasticity. The curvature of this setting varies according to the type of paper. Our machine has a deformable surface under the book, whose shape is curved only in the direction perpendicular to that of the spine and is controlled by changing the positions of multiple rods under a sheet placed on the deformable surface. Fig. 7 shows the details of this part. As shown in this figure, there is also a plate supporting the edge of a book under the sheet. This mechanism can provide a small curvature when the paper is thick and its elasticity is large. In contrast, when the paper is thin, the curvature is set to be small.

Also there is a space under the sheet. As shown in Fig. 8, if the book has a hard cover, the hard cover, as well as

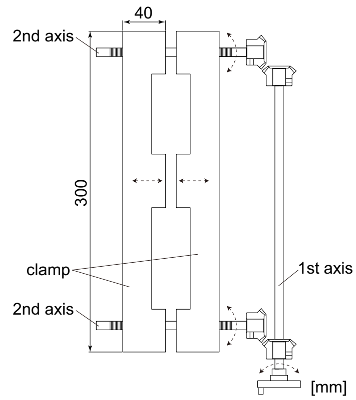


Fig. 6. Configuration of book clamp.

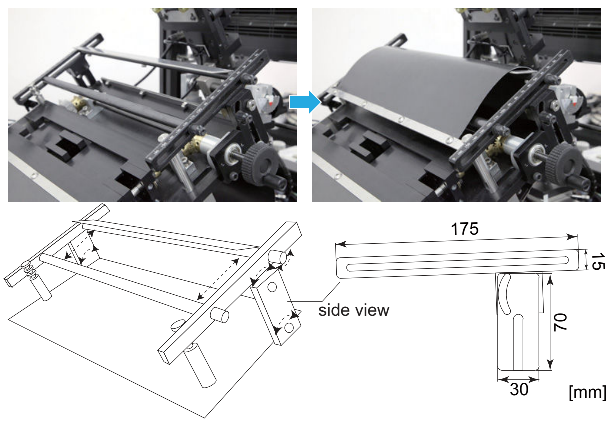


Fig. 7. Holding book page curvature.

some of the pages when the book is thicker than our assumed condition described above, are put in this space.

D. *Page turner manipulator*

The manipulator for turning pages consists of two parts: a head and an arm. The head touches the edge face and manipulates the pages. The arm has two roles, including pushing the head against the edge face to keep its shape and moving the head downward.

1) Head of manipulator: The first role of the head is to curve the pages and to keep the shape of the edge face the same as the shape set initially. The second role is to release each page one-by-one. In order to realize these two functions, the head consists of holder formed of a cylinder of elastic material in planar contact with the edge face and a thin plate, called a "toe", for controlling the release of each page. These parts are attached to a single plate. Fig. 9 shows a design of the head. Fig. 10 shows the developed one.

The toe is thin and spatula-shaped. In this prototype, the thickness was 0.2 mm, and it was made of stainless steel. Introducing a deformable material allows us to compensate for the lack of installation accuracy, which requires keeping parallelism between the tangential direction of the edge face of the book and the moving direction of the head. Also, the toe is approximately triangular and is rounded to prevent damaging the book. In this prototype, the rounded end of the toe was a circular arc whose radius was 3 mm.

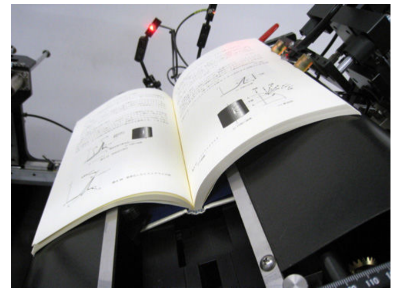


Fig. 8. Holding a hardcover book.

Fig. 4 shows the force generated by setting this part on the edge face. As shown in this figure, it is difficult for this toe alone to hold many pages so that upper pages are easily moved. Using the cylindrical holder to hold a few pages behind the toe avoids this problem. The holder holds the pages and keeps them curved. This configuration is more effective at maintaining the shape of the edge face during book flipping. In this prototype, we used a polyurethane rubber cylinder whose radius was 12 mm. Also, as shown in Fig. 9, there were two holders at the sides of the toe in order to apply a uniform force to the edge face. The toe and these two side holders were mounted to the same plate. Thus, these parts moved at the same speed according to the plate motion.

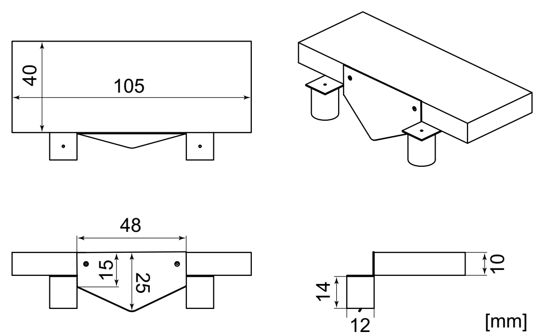


Fig. 9. Details of page turner head.

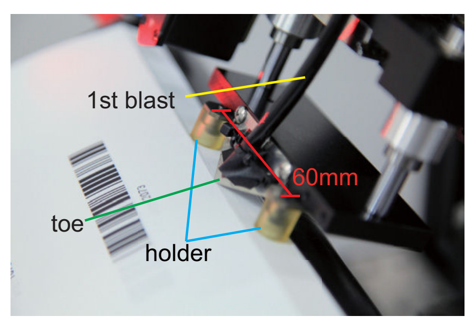


Fig. 10. Page turner head.

2) Arm parts of the manipulator: The arm of the manipulator has a part that presses the head against the edge face and a drive mechanism for moving the head. Fig. 11 shows the configuration of this part.

The manipulator needs to hold pages with a constant pressure according to the elasticity of the remaining pages while flipping the book. To meet this demand, we use air

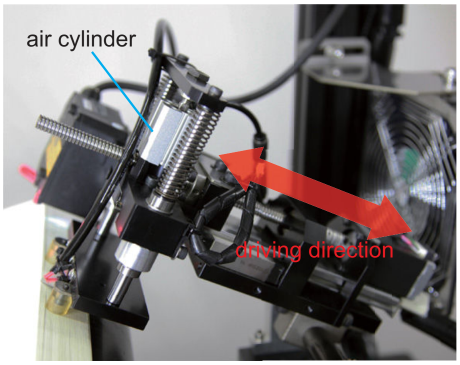


Fig. 11. Conveyor of the page turner head.

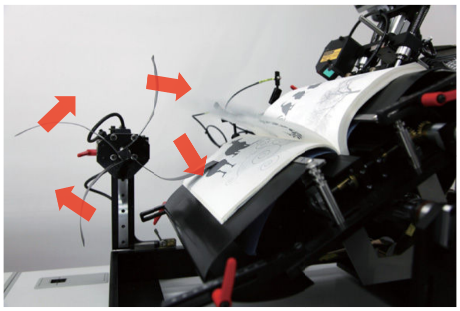


Fig. 12. Retainer for the turned pages.

cylinders for the part that pushes the head against the edge face. In the developed system, we experimentally employed to push at 40 N. Although this condition should be changed according to the type of book technically, the experiments shown in Section IV was achieved in the same setup. Also, in order to construct the part that moves the head in the direction perpendicular to the lengthwise direction of the book spine, we introduce a linear drive mechanism consisting of a ball screw and a linear guide. This drive part is designed to allow its direction to be changed. The direction is adjusted with the bottom face of the cylindrical holder described in the previous section, which is parallel to the edge face.

The precision of the drive system needs to be less than the distance between pages l. This length l is longer than the thickness of the paper m, as shown in Fig. 4. Specifically, the thickness of the paper in the target book in this machine is assumed to be over 50 μm. In the developed machine, we employed a drive system whose precision was 2 μm per step, which is considered to be sufficient for accurate flipping. In addition, the driving range is 120 mm, which is also suitable for the target books, since we assume that the maximum book thickness is 50 mm.

E. Air blast to assist flipping

The released page is turned to the left by air blasts in three stages. Fig. 5 and Fig. 9 show the positions of these air blasts. The first blast is blown via a nozzle into the space between the released page and the pages held by the manipulator. This is used to separate the free page and the held pages. This blast comes from above the toe of the manipulator and moves only the page released from the manipulator. The second blast comes from the right side of the machine in order to

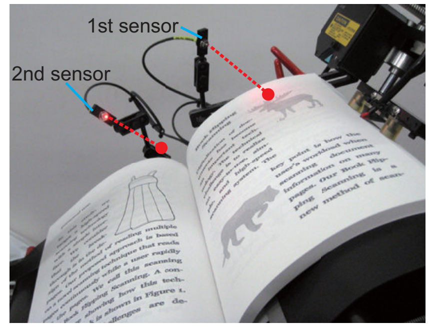


Fig. 13. Configuration of sensors controlling the retainer for the turned pages.

flip the separated page to the left side of the machine. The third blast comes downward from above the machine. This prevents pages from rising again to the center in the case of books having thick paper and small books. These second and third blasts are generated by fans. In the developed system, the air volume of the 1st blast was 8.5×10^{-5} m^3/min. The air volume of the 2nd blast was 4.5 m^3/min. The air volume of the 3rd blast was 2.3 m^3/min. These conditions were decided experimentally.

F. Retainer for turned pages

Together with the third blast, moving vanes of the retainer hold the turned pages in order to keep those pages down. As shown in Fig. 12, once sensors detect the passage of a page, the vanes are rotated to hold the page. The detection method is described in detail in the next subsection. As described above, it is important for book digitization not to occlude the book from the camera. Therefore, this retainer is set below the digitized area, which is the area where the page is not curved by a large amount and is observed with small distortion by the camera.

G. Measurement of the turned pages

This machine detects the moment at which each page released by the manipulator rises and the moment that it turns to the left side of the machine. The rotation of the retainer for the turned pages is controlled based on the detection of these moments. In the developed machine, we used two fiber sensors that detect the passage of an object within the measured area by measuring the reflected light. The response time of the sensors used was 1 ms.

Fig. 13 shows the installation positions. The first sensor faces the left-hand page. The rising of the released page is detected by measuring the change in the distance between the sensor and the page, which is obtained based on the change in the reflected light brightness. Similarly, the second sensor is mounted on the left side of the machine and detects when page flipping is completed.

IV. Performance Evaluation Tests

We performed two types of evaluations. In the first experiment, we tested the performance under different system configurations. The results showed that the integrated

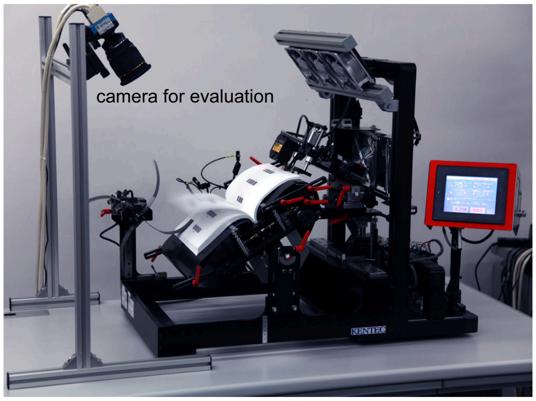


Fig. 14. Experimental setup.

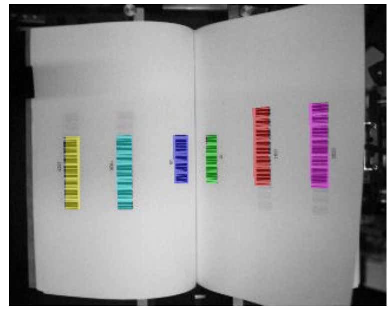


Fig. 15. Examples of the detected barcodes on the page.

TABLE I
PERFORMANCE EVALUATION UNDER FOUR DIFFERENT SYSTEM CONFIGURATIONS.

System configuration	number of trials	average velocity [pages/min]	average success rate [%]
proposed configuration	10	314	100
without 1st blast	10	309	99.2
without holder	10	-	56
without toe	10	339	88.8

mechanisms demonstrably contributed to the flipping performance. In the second experiment, we tested the performance variations with different books. The results showed that our machine operated properly with the various books.

A. Evaluation under the different system configurations

1) Method: In this experiment, the flipping speed was set to about 300 pages/min. Assuming an actual book digitization system, the evaluations were performed by using a high-speed camera set above the machine. The experimental setup is shown in Fig. 14. The resolution of the camera was 1,280 $\times$ 1,024, and the frame rate was 500 fps. Also the experiments were achieved in the normal indoor condition (temperature: 15-20 degrees; humidity: 30 %).

The flipping performance was automatically evaluated by using a specially made book in which barcodes were printed. We printed barcodes on both sides of the pages, and the stack of paper was bound by a professional bookbinding company. The barcodes were printed at three positions, as shown in Fig. 15. Each barcode allowed us to identify the page number. The basis weight of the paper used was 80 g/m^2, the thickness of the paper was 100 μm, the total number of pages in the book was 200, and the paper size was B5.

In this experiment, if the three barcodes on a single page were observed in a captured image, we recognized the page as being successfully flipped. Under this condition, the success rate is defined as the ratio of the number of pages that are judged as being successfully flipped to the total number of pages. Also, as a result of a preliminary experiment, we confirmed that incorrect barcode identification did not occur.

In the experiments, we evaluated the performance under four system configurations: the proposed configuration, a configuration without the first air blast (Section III-E), a configuration in which the head had only the toe but no cylindrical holder (Section III-D.1), and a configuration in which the head had only the cylindrical holder but no toe (Section III-D.1). We made 10 trials for each system configuration, so that the total number of trials was 40.

2) Results: Fig. 15 shows an example of the observed image during flipping. Barcodes were successfully detected in this image. The rectangles drawn on the barcodes show the detected areas. Table I shows the results of evaluating the flipping performance. The configuration including all of the proposed mechanisms achieved 100 % success rate at over 300 pages/min. This configuration was better than the configuration in which only the toe or only the cylindrical holder was used. This shows the effectiveness of using both of these mechanisms. Also, we confirmed that the first blast contributed to a slight improvement. Book digitization requires a success rate of almost 100%. Therefore, even this small improvement is important, and this mechanism must be provided. In the configuration where the manipulator had only toe but no cylindrical holder the flipping speed could not be determined because the machine could not hold the pages stably, causing multiple pages to be frequently flipped at the same time.

Fig. 16 shows the duration for each page recognized as being successfully flipped in a trial using the proposed configuration. Although the moving speed showed some variations from page to page because the distances between pages were not slightly uniform, multiple pages were not flipped simultaneously. These results show that our machine meets the requirement for high-quality book digitization. In Fig. 16, we can find one page whose duration is clearly longer than the other pages. This is because the book used in the trial had the characteristic that, in the open state, the first page tended to remain open for longer. In practice, the frame rate was 500 fps, so that the temporal difference between this page and the other pages can be calculated to be about 1 s.

B. Evaluation using different books with different types of paper

1) Method: Using the configuration that showed the highest performance in the experiments described above, we performed an experiment with different books. The target books were two books originally made by ourselves and two purchased books. The self-produced books were made

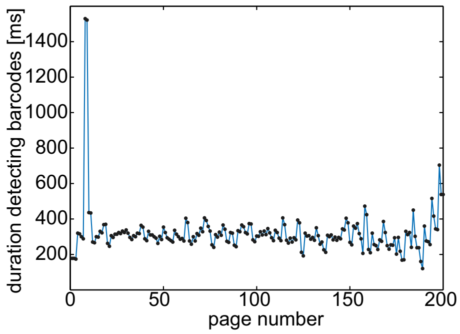


Fig. 16. Duration detecting barcodes for each page.

by the same method as described above. The two self-produced books consisted of thin paper (basis weight: 64 g/m^2; thickness: 60 μm; size: B5; total number of pages: 250) and thick paper (basis weight: 128 gm/m^2; thickness: 150 μm; size: B5; total number of pages: 224), respectively. The purchased books were a hardback book (ISBN: 978-4130621410; size: 21.4 cm $\times$ 15.6 cm; total number of pages: 216) and a paperback pocket edition (ISBN: 978-4121501950; size: 17.4 cm $\times$ 10.8 cm; total number of pages: 192).

In this experiment, markers such as barcodes which would have enabled easy and automatic evaluation were not printed on each page. Therefore, we recorded the flipping of all pages and visually checked the page numbers originally printed in the books in order to recognize which pages were flipped. If the four corners of a page were observed at the same time in a captured image, we judged that flipping was successful. Examples of the observed images are shown in Fig. 17. We performed five trials for each book. The total number of trials was 20.

2) Results: Table II shows the results for the four books. The average speed and the average success rate for the thin-paper book was 301 pages/min and 100 %. For the other books, the flipping speed and success rate were over 300 pages/min and over 98 %, respectively. These results show that our machine worked effectively with books having different paper basis weights.

The reason why a 100 % success rate could not be achieved for the books other than the thin-paper book can be considered as follows. In the case of the thick-paper book, although the flipping was performed stably, the problem where multiple pages were flipped at the same time happened when the number of remaining pages was small. We consider that, at the last page, the edge face and the sheet on the deformable surface were not properly connected, so that the manipulator might have been moved in an undesired direction when the cylindrical holder first reached the sheet. Compared with the thin-paper book, this condition tends to happen more with the thick-paper book because it was difficult, and not required, to strongly curve this book. Possible solutions include modifying the structure of the deformable sheet under the book, introducing a higher-pressure manipulator for keeping the book curved, and placing additional sheets of paper, which will not be digitized, between the last page and the deformable sheet.

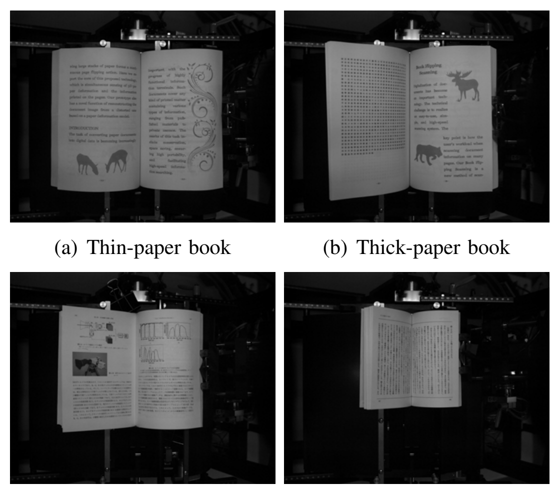
TABLE II

PERFORMANCE EVALUATIONS USING FOUR DIFFERENT BOOKS.

paper quality	number of trials	average velocity velocity [pages/min]	average success rate [%]
thin-paper book	5	301	100
thick-paper book	5	339	98.4
hard cover book	5	341	98.3
paperback book	5	333	99.2

In the case of the hardcover books, the binding was of the round back type, so that it was difficult to keep the edge face strictly planar, and the distances between pages in the edge face were not uniform. Therefore, in the beginning and final phases of book flipping, the problem where multiple pages were flipped at the same time happened. Solutions to this problem include setting a wide page separation by making pages strongly curved, and controlling the movement of the manipulator while observing those distances in the edge face.

In the case of the paperback pocket edition, specific pages had some trouble in being separated, so that the problem where multiple pages were flipped at the same time happened in the same pages. When a book originally has some pages that are stuck together, either because of its natural properties or extraneous matter, it is hard to solve this type of problem using the page turner machine alone. One solution is to introduce a detection and logging mechanism for this kind of abnormal flipping and to rely on manpower to resolve it.



(a) Thin-paper book (b) Thick-paper book

(c) Hardcover book (d) Paperback book

Fig. 17. Examples of the observed images.

V. Conclusion

We designed and developed a high-speed, high-precision, automatic page turner machine for high-speed book digitization. The proposed machine is based on a configuration for turning pages in a contactless manner at high-speed by using the elastic force of the paper itself to recover its shape, assisted by an air blast. Experimental results show that our machine achieved 100 % success rate in page flipping at a speed of 300 pages/min in the case of a book consisting of paper of average thickness. Also, we achieved a 100 % success rate with a book having thinner paper and over 98 % success rate with a book having thicker paper. We confirmed that our proposed machine is a promising technology for realizing both high-speed and high-precision performance for various books.

Future tasks include introducing a sensor feedback mechanism in the manipulation system for more stable page turning operation, so as to enable page-flipping that can be flexibly adapted according to the physical state of the edge face of the book. In particular, we plan to measure the shape of the edge face in real-time and obtain the distances between pages. The movement of the head can be controlled based on the obtained distances. This new configuration will allow us to avoid the problem where multiple pages are flipped at the same time, even when the pages are not uniformly aligned in the edge face, for instance, in books having a round-back binding.

Also it is important to consider an automatic book installation mechanism in order to simplify and standardize tasks performed by a human operator. In addition, we need to consider friction problems for books having thin paper, the detection of abnormal flipping, and problems related to environmental variations, including temperature and humidity.

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