Low Overhead Manipulation of Bound Book Pages

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Abstract—**The robotic manipulation of flexible materials such as paper remains a challenging area of research. Our recent work has focused on the nondestructive manipulation of bound paper as found in books. This article describes a new approach to the one-sided, nonprehensile paper manipulation problem in which we use the polymer Polydimethylsiloxane (PDMS) to create a mechanical bond between the paper and robot manipulator. We have fabricated and tested several complete page-flipping robots that make use of this technique. The current robot has manipulated 10,720 bound pages with an error rate of 0.056%. Future research will focus on refining the design for use in industry.**

Keywords-manipulation, flexible manipulation, sensor-based manipulation, sensor-based diagnosis, nonholonomic manipulation, Polydimethylsiloxane, PDMS

I. Introduction

Manipulation of flexible materials constitutes a challenging area of research because of the complexity of interactions between the part, the part's internal degrees of freedom and the manipulator. In some cases the part's flexibility is an unwanted freedom to be tamed by clever manipulator planning and control [Henrich and Worn 2000]. In other cases the flexibility of the material is essential to the manipulation goals. For example, paper folding represents planning and execution to effect discrete, irreversible changes to the paper's topology by taking advantage of its flexibility during manipulation [Henrich and Worn 2000; Mason et al. 1999].

Of particular interest to us is the manipulation of the paper leaves of a bound book. The goal of presenting each side of every book leaf to the reader can only be accomplished by making use of the leaf's flexibility. Several confounding factors complicate this task. Constraints imposed by the bound leaf edges (i.e. the book spine) introduce hard kinematic limits due to paper's tensile inelasticity, and when combined with the paper's flexibility these characteristics enable stable poses of each book leaf that are undesirable (e.g. a leaf bent down into an S shape). The large variety of paperweight, thickness, surface smoothness, porosity and book dimensions all present challenges to the universality of a particular solution. The possibility of irreversible manipulations (e.g. tearing and creasing) using low force actuation demands special care.

Two insights guide the present work. First, the flexibility of the paper plus constraints imposed by the spine can be actively exploited in order to separate a book leaf from following leaves. Second, because a single side of each book leaf is highly exposed at a time, non-prehensile methods for paper manipulation are particularly well suited to this problem in contrast to more conventional grasp-based techniques that would require access to both sides of the paper.

Finally, then, our goal is to establish highly reliable, non-destructive and reversible techniques for manipulation of bound book pages for a majority of book dimensions and weights. Solutions to this problem have been advertised, but rely upon high-precision effectors for gross page manipulation and active suction for nonprehensile local page manipulation [Kirtas 2003]. Active suction has the potential downside of damaging fragile book leaves and, in the case of porous pages, adhering to more than one page at a time unless secondary excitement is introduced (e.g. air fluffing [Tayler and Yang 2001; Mandel et al. 2003]). In addition, active suction combined with high-precision effectors leads to a high price.

We wish to exploit active sensing and uncertainty-reducing techniques that minimize the need for high precision actuation, leading to what we term *low overhead* solutions [Reshko et al. 2002; All and Nourbakhsh 2001]. In exploring the space of low overhead solutions we have also identified a novel non-prehensile technique for manipulating one side of a book leaf using the polymer Polydimethylsiloxane (PDMS) that, through conformity, achieves a mechanical bond to paper.

The next section presents analyses of our gross-book manipulation technique from the point of view of system topology, as well as details regarding the polymer finger that we have designed. We have built and tested four prototypes of this page manipulation system, and the sections following describe both the third prototype, which costs less than $1,000, and physical experiments performed with the fourth prototype, which have yielded more than 10,720 successful page flips with six errors (0.056% error rate).

II. Model

The process of flipping book pages can be viewed as a series of discrete transitions in a space of possible orderings between interfering robot manipulators and book leaves. We wish to focus on the topology of the required discrete transitions, and therefore introduce a topological system representation below. This is closely related to [Abegg et al. 2000], in which the authors present a systematic approach to manipulating a deformable linear object by capturing the transition graph representing the possible poses of a linear deformable object in contact with a convex polyhedron.

Once the global states are defined, critical points can be assessed and then modeled locally. This leads the analytical focus to the local analysis of the states described in the topological analysis. A complete kinematic model of the overall system would be extremely difficult and time consuming to model with high fidelity and would lead to limited insight. This top-down approach also allows for flexibility in prototype design because the model is independent of the actual physical construction of the robot (it does not matter how the robot moves as long as it achieves the correct topological configuration) and focuses the majority of the analysis on the local subsections of the overall system. In this paradigm the robot is designed to fit the desired system behavior instead of the system behavior being designed around the robot. The next section describes how the system behavior was analyzed in a topological sense.

A. System Behavior

Consider analyzing the sequence of turning a book's pages. The important factor is where each robot arm is located in relation to the pages and other arms. Even more important is the ordering between the various robot arms and pages. We can build a topological map that runs from cover to cover, which designates the ordering of each page and robot arm. This can be conceptualized by creating a semi-circular arc that spans from cover to cover and is centered at the spine. When the arc intersects a page or robot arm, a node is created in a connected graph. This produces a graph that describes the interleaving of the robot's manipulators and the book's leaves. Note that in using this topological representation a single physical manipulator may be represented by multiple nodes if it spans both sides of one or more pages, as described below.

The leaves are defined by whether they fall left or right of the current position in the book; $\mathbf{L_0}$ is the leaf immediately to the left and $\mathbf{R_0}$ is the leaf immediately to the right. The subsequent pages are subscripted down to each cover such that if there are **n** leaves left and **m** leaves right of the current position, then $\mathbf{L_1}$ is the leaf immediately below $\mathbf{L_0}$, $\mathbf{L_n}$ is the front cover, $\mathbf{R_1}$ is the leaf immediately below $\mathbf{R_0}$ and $\mathbf{R_m}$ is the back cover (Figure 1).

The robot requires five arms that interpose themselves between different leaves and/or other robot arms throughout the cycle. **F** is used to manipulate the surface of $\mathbf{R_0}$ to facilitate the isolation of $\mathbf{R_0}$ from $\mathbf{R_1}$. ($\mathbf{S_0}$, $\mathbf{S_1}$) separates $\mathbf{R_0}$ from $\mathbf{R_1}$ and in Step 4 below (Figure 2) is situated such that $\mathbf{S_0}$ is closest to $\mathbf{R_0}$ and $\mathbf{S_1}$ is closest to $\mathbf{R_1}$. The last two arms are **LC** and **RC**, which are used to hold $\mathbf{L_0}$ (and all subsequent $\mathbf{L_i}$) and $\mathbf{R_0}$ (and all subsequent $\mathbf{R_j}$) in place during the flipping process.

Book Terminology
$\mathbf{L_0}$ = Top leaf on left side
$\mathbf{L_1}$ = Leaf below $\mathbf{L_0}$
$\mathbf{L_n}$ = Front Cover
$\mathbf{R_0}$ = Top leaf on right side
$\mathbf{R_1}$ = Leaf below $\mathbf{R_0}$
$\mathbf{R_m}$ = Back Cover

Robot Terminology
F = Manipulates $\mathbf{R_0}$
($\mathbf{S_0}$, $\mathbf{S_1}$) = Separates $\mathbf{R_0}$, $\mathbf{R_1}$
LC = Clamps $\mathbf{L_0} \rightarrow \mathbf{L_n}$
RC = Clamps $\mathbf{R_0} \rightarrow \mathbf{R_m}$

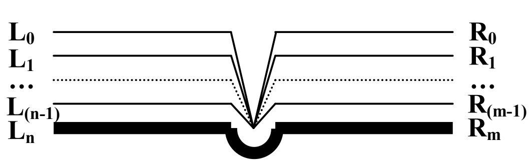

Figure 1: Leaf and Robot notation

The graph produced from the topological map can be translated into a flowchart (Figure 2), which is used to determine critical transitional points, as defined below. This flowchart does not show any of the error checking or sensors of the robot; it is just a physical map of what *must* topologically happen for the page to flip successfully.

The complete page flip consists of six major steps. Step 1 initializes the pages and robot into a startup configuration where the positions of $\mathbf{L_0}$, ($\mathbf{S_0}$, $\mathbf{S_1}$) and $\mathbf{R_0}$ are fixed. The next two steps clamp the left and right leaves of the book down and are independent of each other so they are listed in parallel and denoted 2a and 2b. The ordering of these steps is independent but both steps must be completed before step 3. First inserting LC and RC between S0 and S1 and then moving LC and RC across the thresholds of S0 and S1 respectively accomplish these steps. Next ($\mathbf{S_0}$, $\mathbf{S_1}$) are removed completely. Note that in the above operations there are no paper leaves between **LC** and **RC**. In step 3 **F** is interposed between **LC** and **RC** and then **RC** is removed. Step 4 is critical because an arm is placed between two pages (($\mathbf{S_0}$, $\mathbf{S_1}$) is placed between $\mathbf{R_0}$ and $\mathbf{R_1}$). Finally step 5 completes the flip of $\mathbf{R_0}$ and updates the current position in the book from being between $\mathbf{L_0}$ and $\mathbf{R_0}$ to being between $\mathbf{R_0}$ and $\mathbf{R_1}$. Step 5 also removes **LC** so that it can transition directly to step 2 and close the cycle.

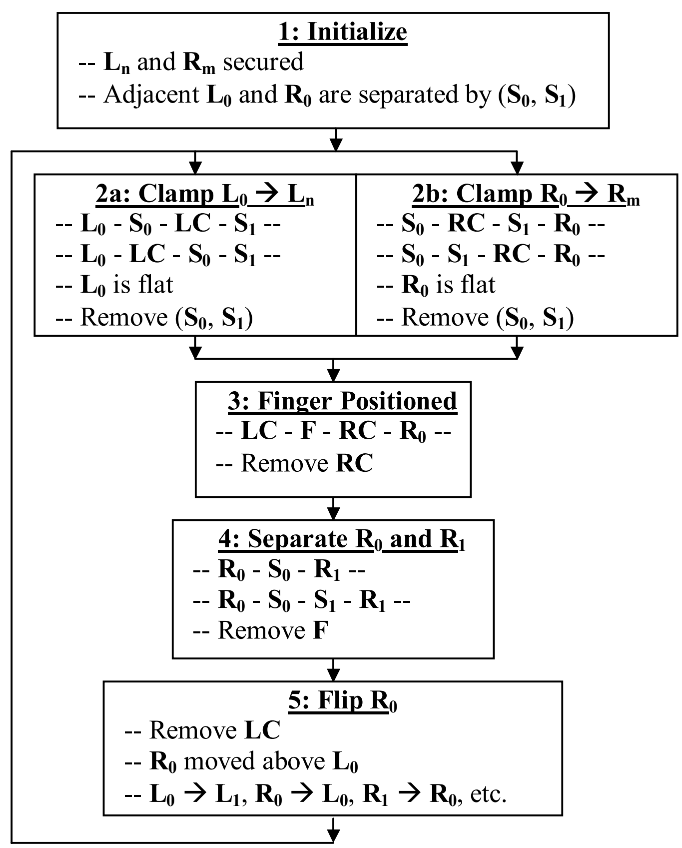

Figure 2: Flowchart of page flip cycle

From this flowchart it is apparent that in all "secure" steps (steps 1-3 and 5) a new robot arm is always inserted between two other arms (the position of the arms is always known). The remaining critical points are the ones in which arms are placed either between different leaves of paper or between an arm and paper. The important critical point in this cycle is step 4 in which ($\mathbf{S_0}$, $\mathbf{S_1}$) are inserted between $\mathbf{R_0}$ and $\mathbf{R_1}$. This is accomplished by locally manipulating $\mathbf{R_0}$ with **F** to force the separation of $\mathbf{R_0}$ and $\mathbf{R_1}$ (or at the very least allow it to be sensed). This basic challenge of separating exactly one leaf of paper from the subsequent leaves is the most critical step. The next section describes our solution exploiting the flexibility of paper and the mechanical bonding of PDMS.

B. Local Manipulation

The topological analysis above identifies one particularly difficult critical manipulation challenge: separation of the top-most right book leaf from the subsequent leaf. We are interested in approaching this problem as a non-prehensile manipulation task focusing upon the single exposed surface of the top leaf. The analysis in this section is intended to characterize the maximum force required to lift and manipulate the top sheet subject to the mechanical constraints imposed by the book spine. We hypothesize that, once fully engaged with the top leaf; the robot can exploit the top leaf's deformability to separate it from the subsequent leaf, which will tend to remain in a lower energy state.

A first simplifying step is to assume that warping and deformation along the axis of the leaf parallel to the spine, which we call the spine axis, may be ignored. Thus consider a book with a spine axis length of zero, each leaf becoming just a deformable one-dimensional (or linear) object. Prior analyses of deformable linear objects are particularly appropriate. [Hirai 2000] presents a model for computing the total energy of a linear object undergoing deformation, using an energy minimization algorithm to find the static pose of such an object under constant load. [Hirai 2000]'s static approach is suitable for our purposes and inspires the analysis below. Dynamics can also be considered [see Remde & Henrich 2000].

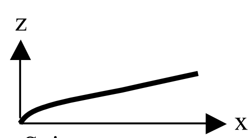

Figure 3: Page Attached to spine

Consider a one-dimensional object with one end constrained in translation, as a joint attached to the book spine (Figure 3). If the object is of total linear length L, then we can denote each point along the object as $P(s)$, with s ranging from 0 to L. We are interested in characterizing the total energy of the object in a specified deformation, and we will consider two sources of energy: flexural energy U_f and gravitation energy U_g. Total energy is the sum of these terms: $U_t = U_f + U_g$. Note that in practice U_f and U_g are not independent and the expressed forces can counteract one another.

Given the weight per unit length of each point $P(s)$, denoted here as $D(s)$, we can compute total gravitation energy:

$$U_g = \int_0^L zD(s)ds$$

Given the bend rigidity of each point $P(s)$, denoted here as $R(s)$, and the angle $\theta(s)$ of the object at point $P(s)$ relative to axis x we can compute total flexural energy using the Kratky-Porod Model:

$$U_f = \int_0^L \tfrac{1}{2} R(s)\left(\frac{d\theta}{ds}\right)^2 ds$$

1) Leaf Separation

Our first question involves the maximum force required to manipulate the top paper leaf of a typical book. Consider for this analysis a high-energy pose in which the paper has been raised and is held high and curved with radius r as depicted in figure 4. For simplicity we assume the spine joint is a perfect joint for rotation and that the paper forms a quarter-arc. While not the absolute minimum energy pose, this shape minimizes U_f, which, in the case of lightweight paper, dominates overall energy.

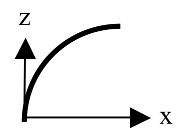

Figure 4: Page Attached to spine

We can now characterize total energy for a book with page length L parallel to the x-axis and page width w corresponding to the length of the spine. Assuming that both bend rigidity R and weight D are constant across the length of the page, the calculation of U_g and U_f simplifies greatly:

$$U_g = \frac{\pi r^2}{4} D \qquad\qquad U_f = \tfrac{1}{2} R\left(\frac{1}{r}\right)^2 L$$

Paper of 92 μm thickness as measured in [Hirai 2000] has a weight D of $7.14w \times 10^{-6}$N/mm and a bend rigidity R equal to $33.7w$ N mm^2, such that b is the page width w. Thus for a typical leaf in the pose shown in figure 4, if r=10 mm, w=25 mm and L=5π mm we compute total potential energy: U_g = 0.0140 N mm; U_f = 66.0 N mm. Thus in a worst-case sense if the page leaf's pose is not a local energy minimum the total energy demanded of the page manipulator to maintain the pose may be as high as 66.035 N mm. In the case of nonprehensile single-finger adhesion to a paper leaf, as described in the following section, our adhesion goal is thus characterized.

Recall that the general goal is to separate the top-most leaf from subsequent leaves. This can be particularly challenging when the spine is not a perfect rotational joint but, rather, imparts some torque, causing the page to lift itself away from the table plane. Figure 5 shows this situation during manipulation of the top leaf. If we assume that inter-leaf interaction is minimal, one can see that for the subsequent leaf U_f will be strictly lower than for the manipulated leaf. Given the relative contributions of flexural and gravitational energy to total energy shown above, this leads us to conclude that the subsequent leaf will likely settle in a low-energy pose significantly less deformed than the manipulated leaf. In practice this means that the deformed and raised manipulation strategy will likely separate the top-most leaf, subject of course to any static friction or adhesion that must be overcome between leaves.

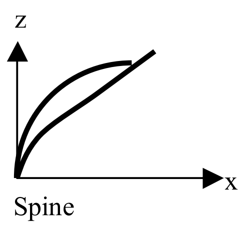

Figure 5: Subsequent page following

The remaining challenge: how does one manipulate the top-most leaf with sufficient adhesion for the energy requirements of the relatively high-energy *separation* pose?

2) Adhering to Top-Most Leaf

Now the goal is to manipulate the surface curvature of the top-most leaf. In general, the edges of the pages of a book are too uneven for prehensile manipulation. This requires a way to hold the top leaf in a non-prehensile fashion. Suction could be used but it has various problems including blow-through (picking up multiple pages), creasing of the pages, and patents [Kirtas 2003]. Another way to approach the problem is to use a substance that sticks to the leaves chemically or mechanically.

Chemical adherence tends to leave a residue on the paper that could have unknown side effects, which leads us to mechanical adherence (without crinkling or creasing the page). Researching in this vein we discovered Polydimethylsiloxane (PDMS), which is widely used in molds for small metal structures and in silly putty. The substance that we are currently exploring is closer in viscosity to that of silly putty (PDMS with clay and other additives) and behaves as a non-newtonian fluid. The benefit of PDMS is that the polymer penetrates the paper fibers and forms a (relatively) weak mechanical bond. Cross-linked polymeric substances have the great benefit of adhering to themselves much better than to other materials, which means that there is a low chance that they will leave any residue on the page. In addition, the properties of the substance can easily be varied so that it holds its shape and only requires a short period of time and pressure to adhere to the paper.

The adherence of PDMS to paper depends mainly on its temperature, degree of cross-linking and the molecular weight of its polymer chains. The mechanical bonding relies on the flow of PDMS into the irregularities of the paper. The bond between PDMS and paper depends mainly on the contact force and the duration of contact. Because of this a robot can be developed which adapts itself to the weight and roughness of a book's pages by varying the pressure and duration based on critical step sensing throughout the cycle.

These constraints heavily influenced the design of the current incarnation of the page-manipulating robot.

III. Robot Description

A. Mechanical

Based on the previous sections, the ideal page-turner would only have the arms listed in the system behavior section (**F**, ($\mathbf{S_0}$, $\mathbf{S_1}$), **LC**, **RC**). This would consist of having a robot with five distinct arms and six degrees of freedom. The **LC** and **RC** only require a single degree of freedom each to be able to clamp the pages. **F** requires at least two degrees of freedom to manipulate $\mathbf{R_0}$ effectively and also to be able to move itself out of the way during other actions (the angle of the contact pad can be scripted into the natural motion of the arm). ($\mathbf{S_0}$, $\mathbf{S_1}$) requires at least two degrees of freedom to separate and then flip $\mathbf{R_0}$.

The third incarnation breaks the separator up into two separate arms (one to flip the page and one to separate the pages) and combines **RC** with the (new) separator. Figure 6 shows the arms of the robot.

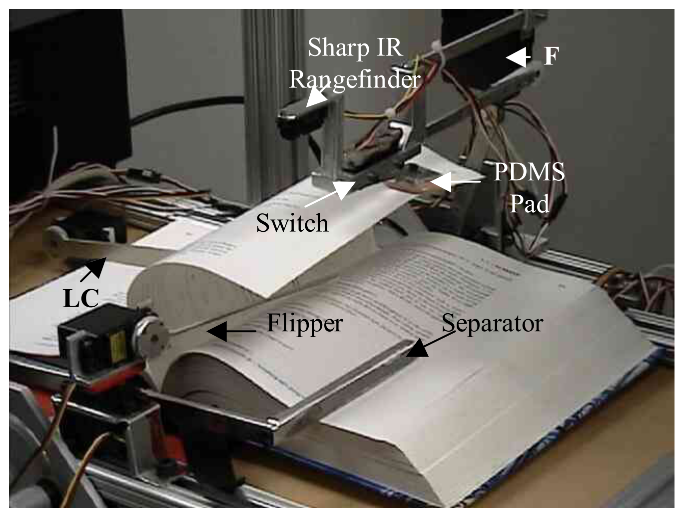

Figure 6: Current prototype of the page manipulating robot. Clockwise in the plane of the book from the bottom right corner the arms are: the separator, the flipper, **LC** and **F**.

This robot uses a two degree-of-freedom parallel linkage **F** (to keep the PDMS pad parallel to the page at all times), a two-degree of freedom right-angle flipper, a single degree of freedom separator and a single degree of freedom **LC**. All of the servos are double ball bearing hobby servos with normal sized servos for all of the arms except **F**, which uses double ball bearing quarter scale servos. All of the arms are made out of machined aluminum.

B. Electrical

The control electronics are simple and consist of a Pic based controller called Cerebellum, which controls all six servos and interprets the analog data from the Sharp IR rangefinder and lever switch.

The rangefinder determines if there is a page above the flipper arm, when it is in the configuration in Figure 6. The switch is mounted directly to the PDMS attachment point and notifies the Cerebellum when the PDMS comes in contact with the book (to allow for varying book thicknesses and for the change in thickness as the page-turner advances through the book). The Cerebellum also has a serial connection, which it uses to output debugging information.

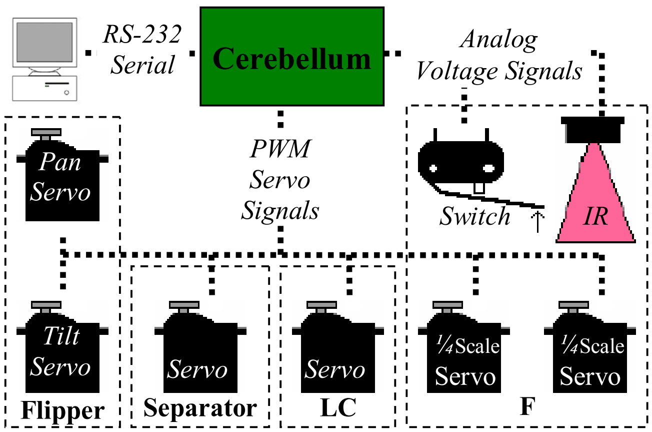

Figure 7: Electrical layout

C. Software

The control code is written in C, compiled using the C compiler C2C and downloaded to the Cerebellum over the serial connection from a computer using a flash PIC programmer (FPP). The code then runs natively on the Cerebellum. An interesting aspect of the code is that the Cerebellum will sense that it is not flipping a page if there is not a page above the flipper arm. It will then try to obtain the page again by increasing the time **F** is in contact with the page. The increased contact time will enhance the force of the bond with the PDMS pad. The code also senses when **F** is in contact with the book so that the robot can keep the pad in a plane perpendicular to the spine to help prevent warping of the page.

IV. Results

Reliability testing was performed with the latest, fourth generation prototype on nineteen books (with a total page count of 10,720). This prototype differed from the third generation by placing all of the arm servo axes inline, parallel to the spine, and incorporating the separator into the manipulation arm. It was also a more robust mechanical design. In this prototype the clamps were separated completely from the manipulation mechanism. The sensing mechanism was simplified to reflectance proximity sensors and the attachment scheme was expanded to multiple attachment points.

The Cerebellum was set up to send the page number back to the terminal via an RS-232 serial line. The Cerebellum started a counter at the first page and incremented the page number by two for each successful flip, which caused the page number returned to match the current page number in the book. This assumed there are no instances in which the robot mistakenly believed that it has flipped a page. Therefore, the only errors were from multiple page flips. This was safe to assume because there was positive feedback via the reflectance sensors as to whether there was at least one page (causing zero-page flips to be removed from the error space completely). The arm adjusted to different book sizes by a manual adjustment when the book was loaded into a V-shaped holder. Book width and thickness were limited by the minimal width (16 cm, 6.25") and maximal thickness (4.5 cm 1.75"). In addition books that contained pictures with dark areas that extended under the reflectance sensors were not analyzed. The final requirement was that the pages were easily bendable (not too stiff, this was rare), of reasonable quality (to prevent ink pickup on the PDMS pads, better than newspaper quality), and not too self sticky, or glossy (again, rare).

The testing procedure started by strapping the covers of the book down using aluminum strips to keep the book in place and reduce changes in spine orientation as the pages of the book were traversed. The robot was then turned on and the arm was adjusted manually using potentiometers to the correct book width and thickness. The PDMS pads were lined up parallel to the spine, relatively close to the edge of the page (within 0.5 cm or 0.25"). Then the number of pages, starting pages, and miscellaneous adhesion force parameters were input via the computer terminal. After the desired number of flips, the robot stopped and held the book open so that the calculated page number could be checked against the actual page number.

The largest influence on time per page-flip cycle was the amount of time it took the arm to guarantee the separation of the pages. The complete page-flip cycle took about twenty seconds, at least ten of which was page separation.

Using this method we have completely traversed nineteen different books (of various sizes and paper types) for a total of 10,720 pages. There were six total multiple-page errors (two pages flipped instead of one) resulting in an error rate of 0.056%. Seven times the robot requested intervention from the user due to pages in undetermined states (0.065% error rate). There were also seven times (0.065%) that it was visually obvious to the operator that an error had or would occur (usually related to misaligning the PDMS cups or a misjudgment in the miscellaneous force parameters input in the initialization step).

The only servos that were replaced in the thirty hours of testing were two clamp servos. The only mechanical failures were, again, in the clamps. In future robot revisions we plan to redesign the clamps and the terminal interface.

V. Related Work

There has been prior research in the autonomous manipulation of flexible or deformable objects, although the flexibility is often viewed as an unwanted degree of freedom that complicates the more conventional manipulation task [Henrich and Worn 2000]. In order to predict object deformations, an important first step is the simulation of deformation dynamics as the manipulator applies varying forces. [Wakamatsu 1997] has developed a dynamic model for the deformation of one-dimensional objects.

A model that has striking similarity to the bound paper manipulation problem is presented in [Schmidt et al. 2001], which focuses on the problem of manipulating one-dimensional objects along a single plane. In [Schmidt et al. 2001] the object has two points of contact with a substrate: one contact point where the object touches an obstacle, and one effect point where the manipulator attaches to the object. If paper warping and lateral flexibility were ignored, we may consider only a one-dimensional slice of the paper from book spine to manipulator finger. Then our machine's polymer finger can be construed as an effect point and the book spine as a contact point where the paper is free to rotate about the spine axis and is constrained to never slide.

The exploitation of paper's flexibility in service of the goal is an important feature of the present book manipulator, and this approach is closest in inspiration to research on the Mobipulator [Mason et al. 1999]. This desktop robot makes use of active paper deformation to enable the Inchworm mode of locomotion. In this mode, pairs of motorized wheels draw paper inward under the robot then flatten the paper to inch the robot forward on a flat surface. In another maneuver that exploits paper flexibility, the Mobipulator can square a single paper sheet relative to a proud table edge by pushing the paper against the edge until the paper flexes up, then releasing pressure by driving off the paper and away from the table edge.

The above work is particularly relevant to the present project due to shared goals of dynamically simple robot solutions that manipulate paper by exploiting paper flexibility and kinematics without dependence on prehensile grasping.

VI. Conclusions

This prototype provides a low cost, low overhead solution to presenting every side of a book's leaves to a reader. Topological systems analysis combined with directed local analysis provides a rich framework that efficiently analyzes the complete page turning cycle. Using the flexural energy of each page and modifying its low-energy state provides a robust solution to separating one page from its predecessor. PDMS is used for non-prehensile manipulation of the page by creating a mechanical adhesion that is more reusable and less likely to leave destructive residue in the book than chemical adhesives. The current prototype has been tested on 10,720 pages with an overall, undetected, error rate of 0.056%.

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References

[1] F. Abegg, A. Remde, D. Henrich, "Force- and Vision-Based Detection of Contact State Transitions," *Robot Manipulation of Deformable Objects*, Eds. D. Henrich & H. Worn, Springer-Verlag, London 2000.

[2] S. All and I. Nourbakhsh, "Insect Telepresence: Using robotic tele-embodiment to bring insects face-to-face with humans," *Autonomous Robots, special issue on Personal Robotics*, (1): 149-161, 2001.

[3] D. Henrich and H. Worn (Eds.), *Robot manipulation of deformable objects*, Springer-Verlag, London, 2000.

[4] S. Hirai, "Energy-Based Modeling of Deformable Linear Objects," *Robot Manipulation of Deformable Objects*, Eds. D. Henrich & H. Worn, Springer-Verlag, London 2000.

[5] Kirtas 2003. Web reference: http://www.kirtas-tech.com

[6] B. Mandel, L. Belkhir, W. Burger, T. Sollitt, S. Miller, E. Kaminker, T. Taylor, "Automatic Book Page Turner for Imaging," US Patent 6,574,014. June 2003.

[7] M. Mason, D. Pai, D. Rus, J. Howell, L. Taylor, M. Erdmann, "A mobile manipulator," *Proc. of 1999 IEEE International Conference on Robotics and Automation*, pp. 2322-2327. Detroit, MI, 1999.

[8] A. Remde and D. Henrich, "Direct and Inverse Simulation of Deformable Linear Objects," *Robot Manipulation of Deformable Objects*, Eds. D. Henrich & H. Worn, Springer-Verlag, London 2000.

[9] G. Reshko, M. Mason, I. Nourbakhsh, "Rapid Prototyping of Small Robots," CMU-RI-TR-02-11. Robotics Institute, Carnegie Mellon University, March 2002.

[10] A. Schlechter and D. Henrich, "Manipulating deformable linear objects: programming using different manipulation skills," *SPIE Int. Technical Group Newsletter, Robotics and Machine Perception*, Vol. 12, No. 1, March 2003.

[11] T. Schmidt, D. Henrich, "Manipulating deformable linear objects: robot motions in single and multiple contact points," *Proc of the 4^{th} International Symposium on Assembly and Task Planning (ISATP01)*, Fukuoka, Japan, May 2001.

[12] S. Srinivasa, C. Baker, E. Sacks, G. Reshko, M. Mason, M. Erdmann, "Experiments with Nonholonomic Manipulation," *Proc. of 2002 IEEE Int. Conf. on Robotics & Automation*, Washington, D.C., May 2002.

[13] T. Taylor, M. Yang, "Sheet feeding apparatus having an adaptive air fluffer," US Patent 6,264,188. July 2001.

[14] H. Wakamatsu, T. Matsumura, E. Arai, and S. Hirai, "Dynamic Analysis of String Objects Deformation for Their Manipulation", *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, Vol.1, pp.196-201, Grenoble, September 1997.