Pneumatronics for Handling of Books

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Abstract: Usually, the term "library automation" involves all the electronic and informatics aspects of archiving, cataloguing and information retrieval of books and library documents. But the management of modern libraries require also to solve problems related to "mechanical automation", that is the physical handling of books within archive areas. Robotic technologies offer today excellent solutions, applied in fully automated libraries. The paper attempts to give a contribution to the handling of books in existing and conventional libraries and archives, applying low-cost devices. The main results of an original research oriented to solve the problems of automatic handling of books and paper material by means a pneumatronic approach is focused and discussed.

Keywords: Pneumatics, Mechatronics, Automation, Libraries

1 Introduction

The modern management of libraries and archives involve not only informatics aspects, but also location problems of books and of collections of magazines and journals and their efficient handling. Under the term "library automation" is usually included all the computerized procedures designed and developed to automate specific tasks within a library: circulation, cataloguing and acquisitions. Today a catalogue of library's collection is usually organized on computerized cards associated to each book and with sorting procedures by title, author and subject. A call number denotes the item's location, e.g. following the Dewey decimal system. An overall approach of library automation must develop both computerized and mechanical aspects of automation. Computerized automation manages the catalogue automation, with check-in and checkout of books, generation of reports and borrowing, indexing of journal articles and trekking interlibrary loans. Mechanical automation concerns the handling of paper documents, with physical manipulation of books from deposits to user areas and their correct repositioning after the reference. These tasks are today solved, from one side, still manually and, from another side, applying sophisticated and expensive automatic systems. An alternative approach suitable for existing structures could be based on low-cost pneumatronic solutions.

The state-of-art in this field shows different interesting solutions and proposals [1]: new modern libraries all adopt RFID/AMH (Radio Frequency IDentification / Automated Materials Handling) equipments as parts of "new building" designs. These robotized equipments can easily sort and stack up to 2000 books per hour. Significant solutions have been realized, for instance, at the Seattle Public Library and at the University of British Columbia in Canada, or at the Chicago State University in U.S.A. But the application of these very flexible equipments is possible in new libraries or archives, where all the structures (deposits, shelves,..) are designed and integrated with the automatic handling system. Humanoid librarian robots are also proposed for book manipulation and theoretical and experimental analyses [2], [3], [4] and [5] have been developed, investigating also on the vision-tactile-force integration of the robot [6]. But within a lot of existing Italian and foreign libraries and archives approaches oriented to solving mechanical automation problems aren't often considered. Reasons related to logistics, to shelves layout, to spaces for deposits and to available funds, often force to prefer manual operations to mechanical devices. Nevertheless, automatic techniques can give significant advantages: decreasing of waiting time for users, service improvement and reduction of errors and inefficiencies. Today a wide number of modern libraries adopt an "open structure" layout (*Figure 1, a* and *b*): books are directly available within reference rooms and can be brought by the users. But they don't mind of their reposition after the reference. This operation is usually forbidden to the user, in order to avoid location er-

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a)


b)

Figure 1. *Free handling of books in an open library (source: Library of Economy, University of Genoa, Italy)*

rors: staff employees take care of the reposition of books and periodically check their correct placement.

Usually all the book material cannot be contained in library open spaces and periodically a repositioning in remote archives is strictly necessary. For this reason all the libraries have available ware houses in remote locations and use own staff employees to manually move books from


a)


b)

Figure 2. *Manual service within a library*

archives to open user areas and vice versa (*Figure 2, a* and *b*). The procedure is started by the request of the user: the books are usually identified through an informatics sequence of information retrieval. Identification codes allow the research within the shelves. If the book is available in the library's open space the user searches by him the book within the shelves and brings it directly. Then the user can refer the book into the user areas, where specific space facilities are made available (Figure 1). At the end of the reference phase the user leaves the book to the library personnel, taking care of its repositioning. Into wide libraries and archives or when the requested book is not available within local shelves in open libraries, it is necessary to search the book into remote deposits: typical layouts of many existing and conventional structures are shown in *Figure 3 (a* and *b).* Also in these cases staff employees manually manage all the handling phases regarding books.

Storage procedures require the engaging of personnel in repetitive and low rewarding jobs. In addition, the manual handling usually causes a high rate of damage on the book covers.

Starting from these considerations the design of mechatronic procedures able to support the handling of paper material with particular reference to existing libraries has been considered and studied. A low-cost approach is followed, focusing the attention on the problems of automatic pick-up and repositioning of books.


a)


b)

Figure 3. *Examples of archives*

2 Steps for automatic handling

Taking into account the large variety of methods of classification and archiving, some fundamental steps for automatic handling must be considered:

- book identification;
- automatic relationship between book and its location;
- positioning of the handling system in front of the shelf;
- pick-up of the book from the shelf;
- motion towards a transfer unit (e.g. a belt conveyor, connecting the archive to the user area);
- book release;
- book repositioning, from the transfer unit into the shelf.

In order to automatically generate these steps typical parameters identifying books must be considered:

- format: A4, Executive, Legal, 4°, 8°, 16°,...;
- back shape: flat, rounded,...;
- cover material: paperbound, plastics, canvas,...;
- cover structure: rigid, semi-rigid, flexible,...

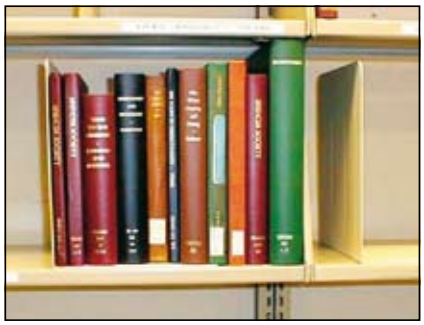
Table 1 synthesizes some formats for standard books.

The serviceable surface for the pick-up of a book located into a conventional shelf is the back. In fact, during the handling phase, the presence of

Table 1. *Book sizes*

Format	Folds	Pages	Size [mm]
in plano, atlante	–	2	over 500
in folio	1	4	over 380
4°	2	8	280–380
8°	4	16	210–270
16°	8	32	150–200

adjacent books doesn't allow to bring the book from other sides. In addition, starting from a proper layout (*Figure 4a*), the picking-up of a book causes displacements of the other ones on tilted positions (*Figure 4 b*).



a)

b)

Figure 4. *Relative position of books*

The manual handling of books involves specific actions and improper removal actions can generate fatal damages (*Figure 5*). This aspect is particularly critical in presence of ancient books.

a)

b)

Figure 5. *Improper removal of a book*

Then proper and improper shelving must be considered: the favorable condition of proper shelving is shown in *Figure 6*. All the books are correctly aligned, each book having different sizes. The distance from two rows is variable and, in order to optimize the archive volume, it can be defined assuming the tallest book as reference. Consequently the suitable surface for handling is the back and the back geometry plays a fundamental role in the pick-up phase.

3 Gripping analysis

The gripping technique must be carefully evaluated in existing libraries, having the cited limits of logistics and internal layout. In addition, particular problems are related to old and ancient books requiring gripping solution able to guarantee their integrity.

The least invasive pick-up technique for handing books is the pneumatics, involving suction cups. Experiences of depression pneumatic systems involving suction cups for different tasks are studied by various authors [7], [8] and [9].

To assure the contact between suction cups and a standard surface is relatively simple: more difficult is the correct contact between a suction cup and the back of a book, because its shape is irregular and the cup operates orthogonal to the back. The book is totally over hanged and its weight generates a torque tending to disconnect the cup. An array of cups must be used and the fundamental problem is related to the optimization of the suction cups unit. Three aspects have been focused and studied:

- forces inducing relative motion between cup and surface (loss of grip condition);
- measurement of the cup strain;
- cup slipping on the surface, without physical separation.

Hypotheses assumed for the preliminary design of the pneumatic grip arm are:

- max. depth of the shelf: 300 mm;
- max. book size: A4 (210 x 297 mm);
- max. book mass: 5 kg;
- max. book thickness: 35 mm.

About the commercial shelves, their size is variable: typical dimensions of preassembled modules are 2 x 0.6 m, 1 x 2 m, 2 x 1 m. In order to test the proposed prototype on shelf modular combinations a robot having a front work area of 3 x 2.4 m has been realized. The easiest method of automation is based on the emulation of the correct manual handling sequence. During a manual pick-up operation phase:

- the hand approaches the book and one finger is used to tilt the book;
- the other fingers grip the book;
- the book is drawn and the manipulation begins.

During a repositioning phase:

- the tilted book approaches the shelf;
- the lower corner is the first to be repositioned;
- the book is rotated and pushed into the shelf.

A preliminary prototype involving an array of ten circular cups, with an additional actuator able to tilt the array, has been conceived and realized (*Figure 7*). The unit is designed in such a way five cups (10 mm of diameter) are able to manipulate the book: *Figure 8* shows the unit assembled on the pneu-

Figure 6. *Typical sequence of books into a shelf*

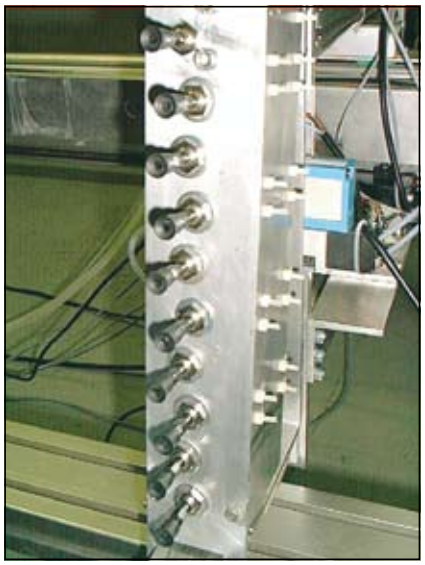


Figure 7. *Preliminary array of suction cups*

matic robot. Improvements have been achieved using eight elliptical cups.

4 Pneumatic gripping optimisation

The gripping unit has been submitted to heavy experimental tests, oriented to evaluate its real behavior. In particular, different kind of covers has been analyzed, investigating on the pneumatic forces generated in the contact between surface and cup. Typical slipping phenomena between cup and surface [11], [12], are considered and submitted to test. *Figure 9* reports results of experiments oriented to evaluate the detaching force vs. different test surfaces, with applied force parallel to the surface (respectively for single circular and elliptical suction cup).

Figure 8. *Unit assembled on the pneumatic robot*

Figure 10 collects similar result with applied force orthogonal to the test surface. These results have been deduced operating at two depression levels: maximum (p_v max), reached supplying the ejectors to 6 bars, and -0.6 bars, reached at 4 bars.

As shown in Figure 10 the performances of the cup array are optimised using eight elliptical suction cups instead ten circular cups. Four cups are able to carry out the book and two separate vacuum supplies (one for four cups) are used: the axial force increases from 8.5 to 21 N. Losses of contact between cup and book are detected by vacuum sensors and the line suction for each

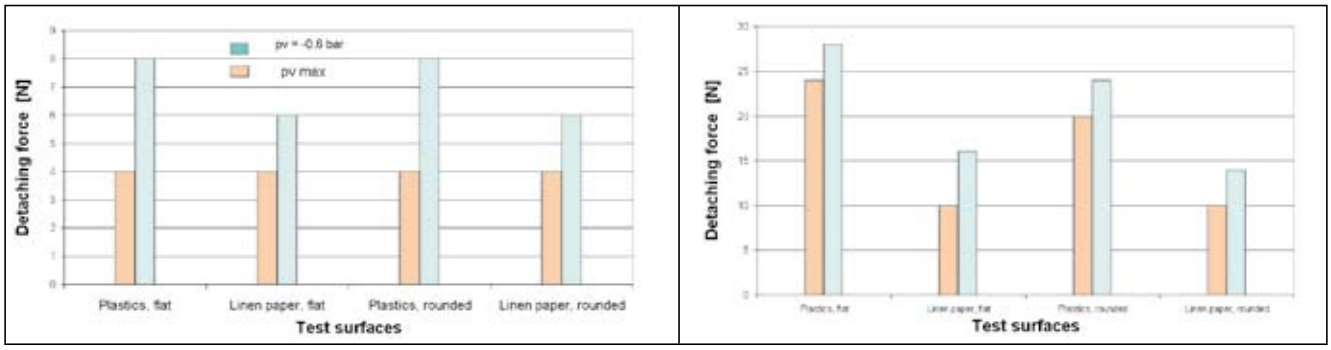


Figure 9. *Detaching force: action parallel to the surface*

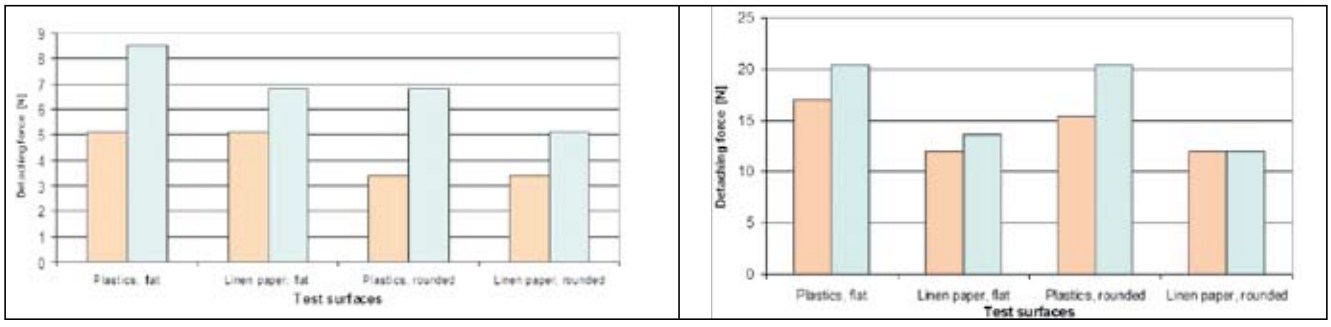


Figure 10. *Detaching force: action orthogonal to the surface*

cup is locked if a loss of contact occurs. Micro-fluidic problems have been focused and solved.

The array is actuated by a couple of pneumatic cylinders, able to move the book forwards and backwards; an additional actuator tilts the array at the beginning of the pick-up phase and during the repositioning.

5 Handling robot

The gripping unit is the end effector of a large size pneumatic Cartesian bi-dimensional robot, been designed and realized in such a way to be easily positioned in front of a shelf: *Figure 11* shows two pictures of this unit.

The prototype essentially consists on a low-cost automatic unit able to be installed in front of existing shelves: but starting from this solution the mechatronic design can be developed integrating the mechanism into the shelf structure.

The proposed bi-dimensional system involves three rod less pneumatic axles: two vertical axles, embedded on precision mechanical guides, are simultaneously moved: a transversal axle carries on the pneumatic end effector. As previously cited, the front working area of the robot is 3 x 2.4 m, compatible with standard geometries of commercial shelves.

The unit is pneumatically driven by a group of on-off spool valves controlled by a modular PLC. Each axle is equipped with a low-cost position optical transducer; their signals are used to switch the valves. PC manages the overall motion procedure. The user digits the data of the book of interest: an internal database correlates the book to its location into the shelf. The corresponding coordinates are used as input to the automatic sequence of motion.

After the gripping phase and before the repositioning phase, the previously described arm must be moved on planes parallel to the front of the shelf. This motion depends on the location of the book: in fact, at the beginning of the automatic manipulation, the gripping arm must be correctly positioned in front of the book to be handled and, when that book goes backs, it must to be repositioned at the correct position.

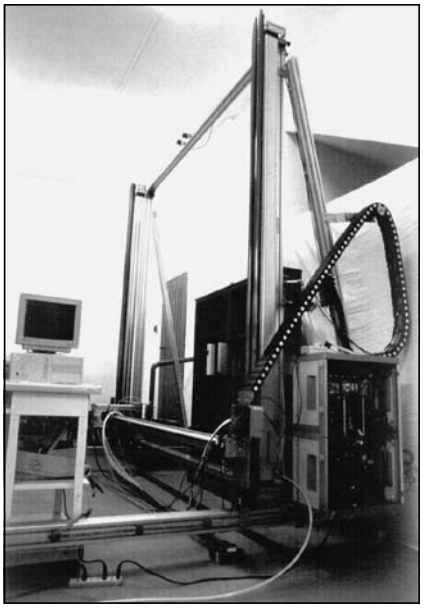


Figure 11. *Two views of the pneumatic robot*

The fundamental reference for the book retrieval consists on its location. Taking into account of the low automation level present in many libraries, two methods for the position identification are tested:

- sequential access, based on the reading of a bar code glued on the back of each book;
- direct access, defined by the characteristic co-ordinates associated to a book. They are function of the number of shelving, of the number of shelf and of the position inside the shelf ("chain" or "call" number).

The sequential access requires a bar code scanner embedded on the pneumatic end effector: differences are related to the type of the bar code used. "Smart" bar codes have the title and local call number printed on the individual bar code; "dumb" bar codes do not. More specifically, "smart" bar codes are usually used in the first stages of automation. They are the product of sending out the shelf list for a retrospective conversion or getting the data back, for instance, in MARC (MAchine Readable Cataloguing) format from any kind of conversion. Direct access can be implemented learning the shelf layout to the manipulation unit. The position of each book is univocally defined from its location mark in the library: the preliminary knowledge of the book dimensions (in particular the thickness) allows the automatic definition of X and Y coordinates of a "driving point" associated to each the book in the frontal plane.

Figure 12 shows a view of the designed pneumatic robot, under assembly in front of a test shelf, smaller with respect to the front working area of the robot. The cross actuator is reinforced with a metallic beam in order to correctly support the weight of the array.

Figure 12. *The pneumatronic unit under assembly*

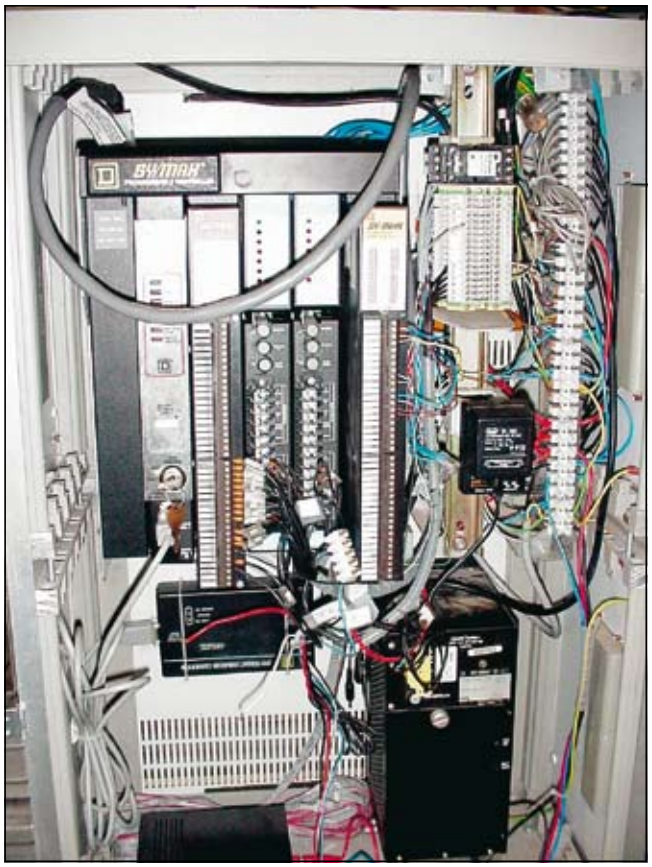


Figure 13. *PLC used for the motion control*

The achieved position accuracy is 2 mm, on a working area of 3000 x 2400 mm: this error is acceptable for the application and it is performed by a modular PLC (*Figure 13*). Input signals arise from end-stroke position sensors on axes (digital), linear position transducers (square waves train), pressure and vacuum transducers (analogue) and bar code scanner. Outputs involve commands to solenoids of valves and ejectors (digital signals).

The programming code is an advanced ladder: the motion is under position control and a generic position is reached by temporised switching of valves. Actual and theoretical positions are continuously compared: the error value is used, into an original motion algorithm, to automatically modulate the actual values of internal pressure of the pneumatic axes.

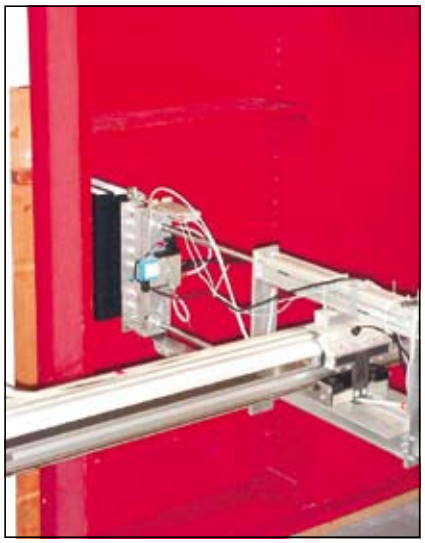
Comparisons with similar problems [13], [14] and [15] have been analysed. A user-friendly interface allows to the user the selection of the required book starting from title, author or subject: an internal database is able to correlate the book to its position on the shelf.
Starting from an initial position (bottom left corner) the mechatronic unit reaches the book to be moved following sequential or direct access approaches. After the book identification, it is gripped, moved and released on a reference, simulating a conveyor tape. The inverse procedure is actuated for the repositioning phase.

Figure 14 (a, b and *c)* reports three phases of handling: pneumatic gripping, manipulation and deposition of the book on a simulated reference platform.

Figure15 shows an intermediate handling phase, with a book under manipulation supported by the suction cups array. Two elastic elements are able to avoid the "flattering" of the book pages during the motion.

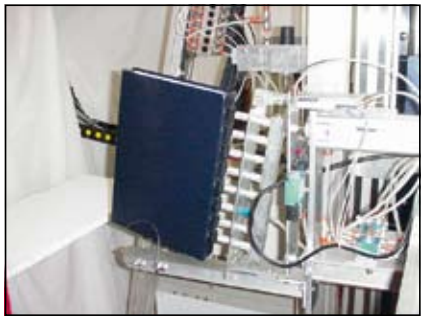
The mechatronic prototype has been submitted to systematic tests, in order to check its reliability. In particular, different areas of gripping and different manipulation speeds are analysed. *Figure 16* reports some results on the percentage of successfully manipulation at different working pressures, corresponding to four different parts of the frontal manipulation area. Books having weight up to 48 N, front area of 210 x 297 mm and thickness up to 35 mm have been tested. The best working pressure seems to be 7 bars, under the condition of four suction cups able to carry on the book. The results of handling in different areas of the workspace have shown some critical working conditions at the bottom right corner.

Considering the worse gripping condition, the maximum manipulation time (including all operation phases) has been detected in about 7 s.
In order to estimate the duration of the overall automatic sequence this time could be doubled or tripled considering the transfer phase from the archive



a)

b)



c)

Figure 14. *Phases of handling*

Figure 15. *View of book supported by the cups array*

area to the user area. It means that in 15 ÷20 s from its informatics selection on a terminal a book can be made available to the user. Similar times are necessary to the reposition of the book into the shelf.

6 Conclusions

The goal of the research activity was the design and the practical realization of a low-cost mechatronic prototype able to automatically manipulate books into existing libraries and archives, taking into account traditional layout, logistics and internal organization of conventional shelves and archive rooms. The classical placement of books into shelves allows possible areas of contact only on the back of the book: for this reason the first step of a correct manual handling approach consists on the inclination of the book, in order to make available parts of lateral surfaces for manipulation. Consequently the design has been implemented attempting to limit the intrusion of the end effector: this aspect is significant also for handling of old or ancient books.

The study has been implemented emulating the manual handling procedure: the proposed prototype is totally pneumatic and its structure is conceived to be easily installed in front to a standard shelf or group of shelves. Pneumatic technology allows a low cost of production with good position accuracy.

The proposed unit is able to handle books of different size, shape and external covers. A smart procedure identifying the book in the shelf is implemented and successfully tested. The bulk main frame makes available a wide workspace, compatible with standard geometries of commercial shelves.

The geometry of the end effector allows the handling of books with a robust array of suction cups: old and ancient books can be successfully manipulated thanks to the not invasive technique. A detailed analysis about the best cup geometry has been developed, in particular comparing circular and elliptical cups.

The mechatronic unit automatically manages all the phases of pick-up and repositioning of a book, assuming that the book is transferred from and to the user area by means a belt-conveyor. Methodical tests on the prototype have shown its performances and limits. Further improvements will involve the enhancement of the book locking during the manipulation phase, in order to avoid possible "flattering" phenomena under high motion speeds and the re-design of shelves with embedded handling units.

In addition, the target is to install the prototype inside an existing library of the University of Genoa, testing the unit under actual working conditions and, if possible, improving the performances achieved in laboratory. The results of these tests will be significant to evaluate the possibilities of an industrial production of this type of device and to deepen the mechanical and structural problems related to the integration between mechatronic equipment and shelve.

Finally, further aspects concerning the integrated design a group of multiple interlaced pneumatronic units, handling of paper materials having irregular shapes and manipulation of non-rigid cover books will be faced and discussed in next papers.

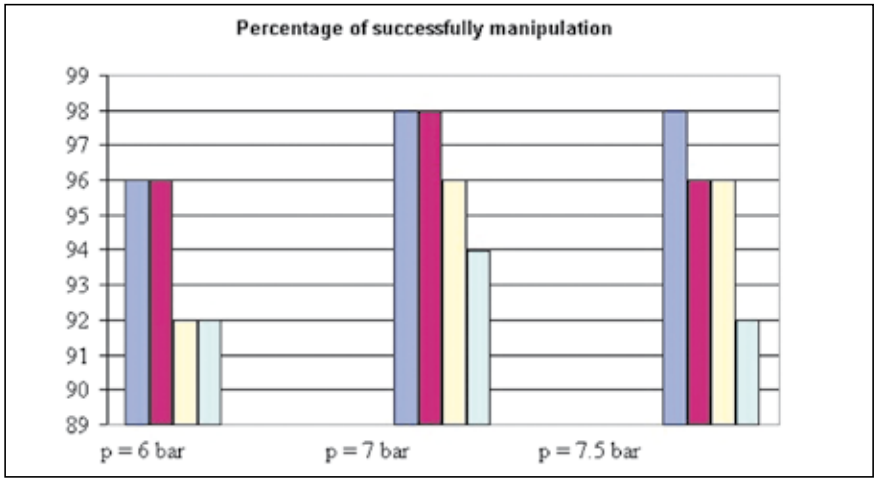


Figure 16. *Success of manipulation (Top left: indigo. Bottom left: violet. Top right: yellow. Bottom right: blue.)*

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Pnevmatronika v stregi knjig

Razširjeni povzetek

Moderno upravljanje knjižnic in arhivov ne obsega samo informacijskih vidikov, kot so avtomatizirano arhiviranje, katalogiziranje in pridobivanje informacij o knjigah ter knjižničnih dokumentih, ampak vključuje tudi naloge določanja lokacije posameznih knjig in revij v skladiščih oz. na knjižnih policah, kakor tudi njihovo učinkovito fizično strego v prostorih knjižnice in arhiva.

»Mehanska« avtomatizacija strege knjig in drugih dokumentov predstavlja fizično manipulacijo knjig iz mesta deponiranja do mesta uporabe in pravilno vračanje nazaj na prvotno pozicijo. V primerjavi z obstoječimi dragimi in kompleksnimi strežnimi sistemi, je v prispevku obravnavan primer cenenega pristopa avtomatizirane strege knjig.

V ta namen je bil razvit prototip cenenega namenskega pnevmatičnega kartezičnega dvodimenzionalnega robota (*slika 11*), nameščenega pred policami, ki omogoča enostavno pozicioniranje prijemalne enote pred knjižno polico oz. knjigo. Prototip kartezičnega robota je zasnovan tako, da je prilagojen obstoječim standardnim knjižnicam in arhivom, upoštevajoč tradicionalno zasnovo tlorisa, logistiko in interno organizacijo konvencionalnih knjižnih polic ter arhivskih sob. Omogoča strego knjig različnih velikosti, oblik in platnic.

Posebna pozornost je bila usmerjena v razvoj ustreznega prijemala, ki omogoča prijemanje različnih knjig in platnic, brez fizičnih poškodb oz. je najmanj invazivno. To je še posebej pomembno pri manipulaciji starih knjig, ki katerih platnice so izjemno občutljive na fizične poškodbe. Zato je bilo razvito prijemalo z vakuumskimi priseski. Analizirane so bile različne geometrijske oblike priseskov (od okroglih do eliptičnih) ter narejeni preizkusi in meritve, ki so omogočili razvoj najoptimalnejše oblike priseska. Primer prijemala z okroglimi priseski in mehanizmom za dodatno nagibanje je prikazuje *slika 7*. Na *slikah 9* in *10* so prikazani rezultati testov in optimizacije sile prijemanja na različnih oblikah in materialih platnic. Na *sliki 12* je prikazan prototip pnevmatičnega robota pred tesno knjižno polico v laboratoriju. Natančnost pozicioniranja robota je 2 mm na delovnem področju 3000 x 2400 mm, kar je sprejemljivo za praktično aplikacijo. Mehatronska naprava samodejno upravlja vse faze prijemanja in odlaganja ter pozicioniranja lnjige.

Glavni cilj raziskave je postaviti prototip robota za strego knjig v obstoječi knjižnici Univerze v Genovi in njegovo testiranje v realnih pogojih delovanja.

Ključne besede: pnevmatika, mehatronika, avtomatizacija, knjižnice