Proceedings of the 2001 IEEE
International Conference on Robotics & Automation
Seoul, Korea · May 21-26, 2001

A New Ultralight Anthropomorphic Hand

S. SCHULZ, C. PYLATIUK and G. BRETTHAUER
INST. OF APPLIED COMPUTER SCIENCE
RESEARCH CENTER OF KARLSRUHE, GERMANY
schulz@iai.fzk.de, pylatiuk@iai.fzk.de, bretthauer@iai.fzk.de

Abstract

In this paper a very lightweight artificial hand is presented that approximates the manipulation abilities of a human hand very well. A large variety of different objects can be grasped reliably and the movements of the hand appear to be very natural. This five finger hand has 13 independent degrees of freedom driven by a new type of powerfull small size flexible fluidic actuator. The actuators are completely integrated in the fingers which made possible the design of a very compact and lightweight hand that can either be used as a prosthetic hand or as a humanoid robot hand. A mathematical model for the expansion of a flexible fluidic actuator is given and the mechanical construction and features of the NewAnthropomorphic Hand are illustrated.

1 Introduction

In the United States 41.000 persons are registred who had an amputation of a hand or a complete arm [1]. With the same frequency of occurrence (1 in 6100) there would be 1.000.000 such persons worldwide. The main factors for a loss of an upper extremity are accidents followed by general deseases and injuries from war. For the individual the loss of an upper limb results in a drastic restriction of function and cosmesis. Therefore in the last 3 decades an increasing number of handicapped persons have been provided with prosthetic hands that have the shape of a human hand and that are actuated by a DC motor with reduction gear trains.

However, surveys on using such artificial hands revealed that 30 to 50% of the handicapped persons do not use their prosthetic hand regularely [2],[3]. The main factors for the rejection of conventional prothestetic hands were:

- **a heavy weight**

although commercial prosthetic hands have about the same mass as human hands they appear to be unpleasantly heavy because the mass is transmitted by a lever arm to the short stump of the amputated arm.

- **a low functionality**

A human hand can perform a large variety of different grip movements while conventional prosthetic hands can only perform a single pincer-like grip movement. Therefore the gripping abilities are restricted, so it is for example impossible to pick up a pinball with the artificial hand. A second limitation of functionality is that the fingers have only one degree of freedom and can not adapt to the shape of an object. The consequence is an increased force, that is neccesary to hold an object stable.

- **a robot-like movement**

The limited DOF's cause the movements to appear unnatural.

To overcome these disadvantages a lot of efforts have been done worldwide. A promising research activity improved the functional range of an electrically driven prosthetic hand by enabling the thumb to be moved independently from the other fingers [4]. As a result a powerful grip (without thumb) and a precision grip (with thumb in an opposing position) can be performed. Hence, as a consequence of the heavy actuators and mechanical elements that have been used the mass of the prosthetic hand has not been reduced.

Other research groups focused on artificial hands that are constructed as an end-effector for a robot-system [5][6]. These robot hands approximate the manipulation abilities and grip force of a human hand already very well, but their control systems are very sophisticated. To grasp and manipulate an object the desired position or torque of each of the multitude of independantly controllable joints must be computed which affords a high-performance computing-system. For handicapped persons the mass of these robot hands is too high. Since the 1950's many research groups developed artificial hands with a fluidic actuator that is called McKibben artificial muscle [7],[8],[9]. The forearm houses the contracting artificial muscles and the force is transmitted via tendons. But in a prosthetic hand there is hardly any space left in the socket that covers the stump of the forearm of a handicapped person.

A new artificial hand that meets the requirements of a improved prosthetic hand is developed at the Forschungszentrum Karlsruhe (FZK). It is based on the so called flexible fluidic actuators. The miniaturized actuators are integrated in the fingers of the new artificial hand (see Fig. 1). This enables the construction of a very lightweight hand with high functionality and human movements. With the new hand the grasping of many objects or tools of different sizes and shapes is possible.

Authorized licensed use limited to: THAPAR UNIVERSITY. Downloaded on August 03,2010 at 04:56:58 UTC from IEEE Xplore. Restrictions apply.

Figure 1: New Ultralight Anthropomorphic Hand

2 Flexible fluidic actuator

Pneumatic and hydraulic actuators are of great practical importance in industrial process control. They are used in a wide variety of different applications, such as heavy industries, mechanical engineering, transportation systems and in medical engineering. The advantages of these actuators are: a robust construction, a high power capacity, a high reliability and a reasonable efficiency [10]. However, conventional actuators only have a small flexibility in their mechanical construction and consequentially have limited movement.

Therefore, a new class of actuators has been developed having the following advantages:

- a high flexibility designed into their mechanical construction
- realization of very complex movements
- a lightweight construction
- very low manufacturing costs.

This class of new actuators will be described now.

2.1 Mechanical construction

A single actuator element consists of a feeding channel for the pressurized air or liquid and a "chamber" which is connected to the two movabale parts of a joint. During the inflation of the actuator element by air/liquid the volume of the element expands and the height of the element vertical to the flexible wall of the chamber increases. This change of distance between the opposite lateral surfaces is called the „expansion behaviour". During this process the volume energy is converted into deformation energy.

2.2 Joint Structure

By using the single actuator elements described above different joint structures can be realised. In figure 2 a joint based on the expansion behaviour is illustrated. By using many fluidic actuator elements together structures with very complex flexibility can be created. Thus making many different and unusual movements possible.

Figure 2: A simple joint based on the expansion principle. The feeding channel is not illustrated

For the effective design of such complex structures it is necessary to derive mathematical models for the expansion behaviour of the actuator elements [11]. Such models enable the deformation properties and the possible force behaviour of a potential structure to be found.

2.3 Mathematical Model of the Expansion behaviour

In order to be able to calculate the force effects of a single actuator in dependence of the inner pressure it is necessary to describe the geometry of the flexible wall of the actuator in the period of deformation by a mathematical model. A single actuator that separates two parallel plates during inflation is an example for a simple linear actuator [see Fig.3].

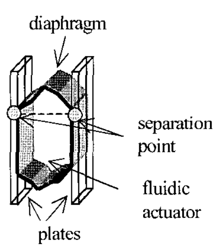

Figure 3: A simple linear actuator

It is assumed that one part of the material presses against the plates while the remaining part stretches a diaphragm between the plates, beginning in the separation points. To obtain the form of the actuator the values were taken for when the volume was at its maximum.

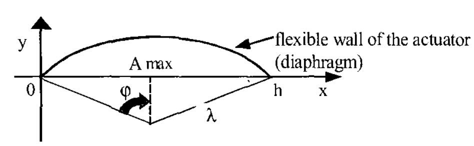

Figure 4: Arc of a circle as maximum area

Authorized licensed use limited to: THAPAR UNIVERSITY. Downloaded on August 03,2010 at 04:56:58 UTC from IEEE Xplore. Restrictions apply.

The corresponding equation for λ can be derived by solving the boundary value problem by means of the Lagrangian multipliers. As a result the flexible walls of the actuator will form ar ~~~ of a circle as given in the following equation, wher(λ stands for the radius.

$$\lambda = \; - \;)^2 + \; \lambda - \overline{?/4})^2 \qquad (1)$$

On the basis of this form, the expansion force on the plates can be calculated as the product of the plate area which is in contact with the fluidic actuator and the inner pressure. The mathematical model for calculating this expansion force is given by the following equation:

$$F = p\left\{\frac{\pi}{4}\left(L - \frac{1}{2}\pi \cdot h\right)^2 + (b - L)\cdot\left(L - \frac{1}{2}\pi \cdot h\right)\right\} \qquad (2)$$

Units

F [N] :	expansion force
p [N/mm²] :	inner pressure
b [mm] :	width of the actuator element
h [mm] :	height of the actuator element between the plates
L [mm] :	length of the actuator element

In order to test the derived model different experiments were performed. In figure 5 the results for three different actuator expansion lengths are illustrated.

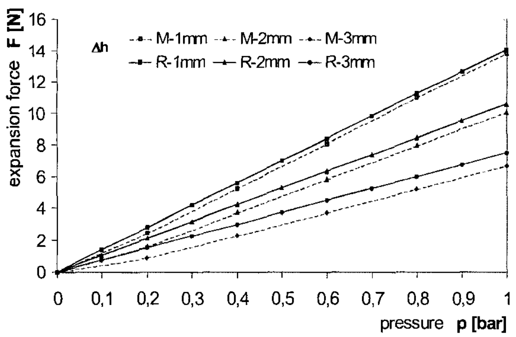

Figure 5: comparison between the experimental (broken lines) and mathematical model (unbr~~~ lines) results for three different expansion length: ΔL. (actuator specification: PP-film, E: 271 N/mm², L: 10mm, b: 20mm, d: 50μm, μ: 0,4)

Fro~ ~e results in figure 5 it can be concluded that:

- there is an approximately linear relationship between the inner pressure p and the expansion force F
- the mathematical model gives a good approximation for the calculation of the expansion properties.

These results show that the mathematical model developed gives the possibility to obtain realistic data for the design of a real actuator [11]. This first practical experiments confirm the effectiveness of these fluidic actuators.

3. New Ultralight Anthropomorphic Hand

3.1 Mechanism and Design

A conventional powered prostehtic hand usually consist of an energy source, one or two actuators, a simple control unit and the mechanical construction. All components except for the myoelectric sensors and the energy source have to be in the hand itself because in the socket there is very litle space left. So we integrated a total of 18 miniaturized flexible fluidic actuators into the mechanical construction of the fingers and the wrist of the hand. Our aim was to mimic as closely as possible the geometry of an male adult human hand.

The new hand can be devided into 2 (+1 optional) sections :

• Fingers: they contain the flexible fluidic actuators that lead to a flexion of the finger, flex sensors and touch sensors (see Fig. 6).

• Metacarpus : provides enough space to house a microcontroller, microvalves, the energy source and a micropump.

• Wrist (optional): also contains flexible fluidic actuators that bend the wrist.

The extension of the joints is done passively by elastomerical spring-elements.

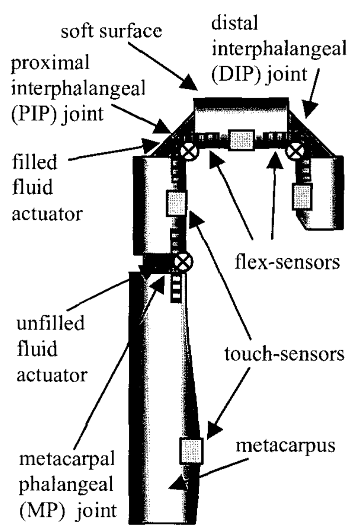

Figure 6: Schematic construction of a finger

Authorized licensed use limited to: THAPAR UNIVERSITY. Downloaded on August 03,2010 at 04:56:58 UTC from IEEE Xplore. Restrictions apply.

3.2 Control

The control system of the human body is of a hierachical order. This is very useful, for we do not have to be conscious of every single step of a movement we want to perform. A large variety of motion patterns are memorized at the cerebellum, so if we want to grasp an object we use these patterns to control the position and torque of every joint. A comperable concept is used to control our hand: having chosen a certain type of grasping the artificial hand performs the pattern of movements.To hold an object stable the precise torque and position of the joints do not neccesariliy be known, because of the self-adaptable properties of the hand. This simpifies the control drastically.

3.3 Self-adaptability

The flexible fingers of the new hand are able to wrap around objects of different sizes and shapes. Because of the elastic properties of the actuators the contact force is spread over a greater contact area. Additionally the surface of the fingers is soft and the friction coefficient is increased by the silicone-rubber glove, that covers the artificial hand. The result is a reduced grip force is needed to hold an object [12].

As a side-effect from the softness and elasticity of the hand it feels more natural when touched than a hard robotic hand and the risk of injury in direct interaction with other humans is minimized.

3.4 Characteristics

Only lightweight materials are used for the mechanical construction of the fingers and the wrist so that each finger weighs less than 20 grams. This makes possible to reduce the mass of a new artificial hand to 50% of the mass of a conventional prosthetic hand.

The time for a complete flexion and extension of a finger is less than 100 ms. Therefore it is possible to open and close the hand with a frequency that is >5 Hz. This is 10 times faster than a conventional protheses [13].

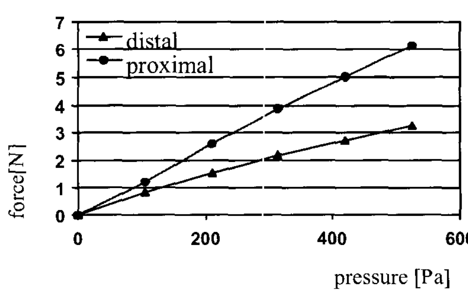

Figure 7: Force of a single finger

The force that was performed by a single finger is illustrated in Fig. 7. It depends on the pressure the actuators were filled with. The maximum force at a pressure of 525Pa was more than 6N between the DIP and PIP joint (proximal) and more than 3N at the fingertip (distal). The resulting force at the fingertips for the whole hand is 12N which is sufficiant to perform most tasks [4]

An aim for the developement of a new artificial hand was to approximate the range of motion of a human hand very closely. Each finger has 3 joints (see Fig. 6). The joint that connects the fingers with the palm is called metacarpal phalangeal (MP) joint. The joint in the middle of the finger is called proximal interphalangeal (PIP) joint and the one that is closest to the fingertip is called distal interphalangeal (DIP) joint. Alike the human hand The movements of the PIP-joint and the DIP-joint are coupled, so each finger has 2 independant DOF.

The range of motion of a single joint is illustrated in Fig. 8. It is similar for the 3 joints of the finger. The flexion of the joint depends on the pressure that takes effect on the flexible fluidic actuator. To obtain the maximum range of motion for a complete finger the parameter has to be multiplied by 3. The design of the thumb is different from the fingers. It has a 3-dimensional base joint that permits an adduction towards the index finger and an opposing towards the other fingers. It also contains 2 coupled joints for a flexion-movement.

The wrist is also flexible and a rotation of 30 degrees in each direction can be achieved

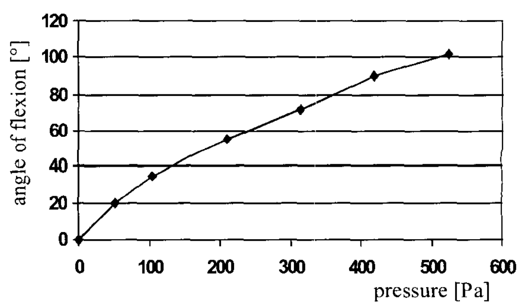

Figure 8: The angle of flexion for a single joint

The most common grasp types can be performed without contact to an object. The grasp types can be devided into power grasps and into precision grasps [14]. Examples are illustrated in Figure 9-15.

Authorized licensed use limited to: THAPAR UNIVERSITY. Downloaded on August 03,2010 at 04:56:58 UTC from IEEE Xplore. Restrictions apply.

Power-grasps:

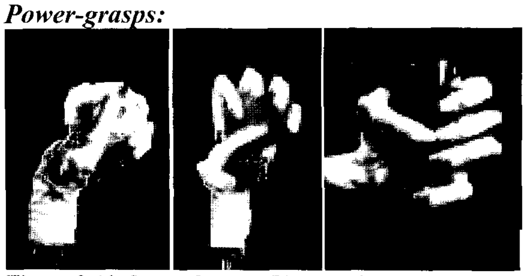

Figure 9-11: Lateral grasp (l.), spherical grasp (m.), cylindrical grasp (r.)

Precion-grasp:

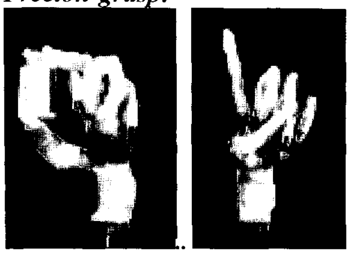

Figure 12,13: Tripod grasp (l.), movement of a single finger (r.)

Details of finger flexion:

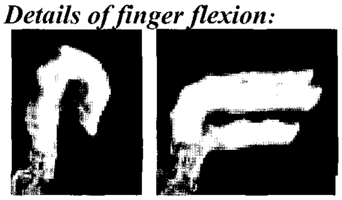

Figure 14,15: DIP and PIP-joint (l.) and MP-joint (r.)

4. Conclusion

In this paper the concept and the design of the New Ultralight Anthropomorphic Hand are presented. It is able to grasp many different objects and the movements appear to be very natural. The motions are based on flexible fluidic actuators. All of these very compact and lightweight actuators have been integrated completely into the fingers of our artificial hand. The palm of the hand remained empty and provides enough space for a micropump. Because of the self adapting properties of the fingers many different objects can be grasped without sensory information from the hand. This enables the developement of a low-mass prosthetic hand with high functionality. A batch production for several expositions of the new hand proved the function to be reliable.

Another field of application for the new artificial hand is found as a soft gripper of a mobile service robot to help old and disabled people. As the whole mechanical construction is very soft, the risk of accidents in direct interaction with humans can be minimized. The New Ultralight Athropomorphic Hand based on flexible fluidic actuators uncloses new perspectives in the developement of humanoid robots.

References

[1] LaPlante, M.P.;Carlson, D.: Disability in the United States; Prevalence and Causes, 1992. Report No.7, Disability Statistics Center, University of California, San Francisco, Jan. 1996

[2] Silcox, D.H.; Rooks, M.D. et al.: Myoelectric Protheses.The Journal of Joint and Bone Surgery, Vol. 75-A, No 12, pp. 1781-1791, 1993

[3] Atkins, D.J.; Heard, D.C.Y.; Donovan, W.H.: Epidemiologic Overview of Individuals with Upper-Limb Loss and Their Reported Research Priorities. J. of Prosthetics and Orthotics, Vol. 8, No1, pp. 2-11, 1996

[4] Kyberd, P.J.; Evans, M.; Winkel, S.te: An Intelligent Anthropomorphic Hand with Automatic Grasp. Robotica, Vol. 16, pp 531-536, 1998

[5] Hirzinger, G.; Butterfass, J.; Knoch, S.; Liu, H.: DLR`s Multisensory Articulated Hand. 5th Int. Sympos. on Experimental Robotics, S. 28-34, Barcelona, Spanien; 1997

[6] Jacobsen, S.C.; Iversen, E.K.; Knutti, D.F.; Johnson, R.T.; Biggers, K.B.: Design of the Utah/MIT dextrous hand. IEEE Int. Conf. on Robotics and Automation, San Francisco, pp 1520-1532, 1986

[7] Shadow Robot Project: Biomorphic Arm, http://www.shadow.org.uk/projects/addprojects.shtml

[8] Lee, Y.K.; Shimoyama, I.: A sceletal framework artificial hand actuated by pneumatic artificial muscles, Proc. IEEE Intl. Conf. on Robotics and Automation, Detroit, Michigan, May, 1999

[9] Chou, C.P.; Hannaford, B.: Measurements and Modelling of McKibben Pneumatic Artificial Muscles. IEEE Transactions on Robotics and Automation, Vol. 12, No. 1, pp. 90-102, Feb.1996

[10] Hollerbach, J.; Hunter, I.; Ballantyne, J.: A Comparative Analysis of Actuator Technologies for Robotics. In: Khatib, O.; Craig, J.; Losano-Perez (Eds.): The Robotics Review 2, MIT Press, Cambridge, MA, pp. 299-342, 1992

[11] Schulz, S.; Pylatiuk, C.; Bretthauer, G.: A New Class of Flexible Fluidic Actuators and their Applications in Medical Engineering. Automatisierungstechnik Vol. 47, No. 8, pp. 390-395, 1999

[12] Shimoga, K.B.; Goldenberg, A.A.: Soft Materials for Robotic Fingers, IEEE Int. Conf. on Robotics and Automation, Nice, France, pp 1300-1305, 1992

[13] OTTO BOCK, Orthopädische Industrie GmbH & Co, Myoelektrische Armprothese, catalogue, Duderstadt, 1996/97

[14] Napier, J.R.: The prehensile movements of the human hand. J. Bone Joint Surg. 38B (4), pp. 902-913, 1956

Authorized licensed use limited to: THAPAR UNIVERSITY. Downloaded on August 03,2010 at 04:56:58 UTC from IEEE Xplore. Restrictions apply.