A Humanoid Muscle Robot Torso with Biologically Inspired Construction

Ivo Boblan and Andreas Schulz
Technische Universität Berlin, Fachgebiet Regelungssysteme, EN 11
Einsteinufer 17, D-10587, Berlin, Germany
{boblan, schulz}@control.tu-berlin.de

Abstract

Human-like robots combine the optimized biological morphology and functionality of the real human with the mechanical constraints and limitations in the creation as well as possible. This will be a trade-off at all times. The best biological solution of a detail is often simple in the function but too complex for the technical analogue. The technical materials are often missing what make a one-to-one copy impossible. The combination of biology and robots leads to smoother and compliant movement, which is more pleasant for us as people. Biologically inspired robots embody no rigid movement, which are made possible by special joints, or actuators, which give way, and can both actively and passively, adapt stiffness in different situations.

This paper present the humanoid muscle robot torso called "Zwei-Arm-Roboter" ZAR5 in human-like proportions and functionality, which is fully actuated by artificial air muscles. The first section gives a short introduction as to how Bionik engineers think in terms of compliant machines and whose technical realisation. The second section looks briefly at mechanical aspects, limitations and constraints and furthermore describes the human-like anthropomorphic five-finger hand. This section also comprises a short view of the used fluidic muscle actuators of the company FESTO[1]. Section 3 describes the electronic components and the decentralized control architecture, which fulfils the requirements on an evolvable control. The last section concludes the paper.

1 Introduction

Bionik is a powerful field of engineering science concerned with decoding 'inventions' made by living organisms and utilising them in innovative engineering techniques. Bionik is a made-up word that links biology and technology. However, nature does not simply supply blueprints, which can merely be copied. Findings from functional biology have to be translated into materials and dimensions applicable in practical engineering.

In order to build humanoids we have to look at individuals in nature with the same proportions and environmental conditions and try not to scale the joints of a beetle, for example, which were not designed to carry heavy weights. Nature always develops optimally, based on the respective surroundings conditions. A parakeet in the jungle is subjected to different conditions than an eagle living in high mountainous regions. The law of survival of the fittest determines natural selection and consequently how the individual adapts to its living space. The parakeet, for example, is not optimised to cover long distances, but rather to be beautiful and to appeal the females.

What can we learn from nature about morphology and physiology for the design of humanoid robots? If we concur with the law of survival of the fittest, then we believe that only optimised individuals can exist in nature in their respective surrounding conditions. Bionik initial task is to search for individuals in nature, which have the same characteristics as the object to be developed. In our case, we are searching for a model of a humanoid robot arm and hand. We are thus looking for animals which are able to hold and/or carry several kilograms and which have human-like proportions with respect to weight and inherent compliance. When looking at the problem more closely, the intrinsic problem is how we can produce a multiple of force, which is able to hold objects that are heavier than their own weight. This is a so-called power-weight ratio; this ratio is about one to one for electric motors. We have found other solutions for actuators in nature, particularly linear actuators that produce tractive force. The power-weight ratio of these actuators is multiplicatively higher than those known for technical actuators. Thus, it seems that nature has a better solution for our technical problem under the given terms and conditions.

We will focus on human-like robots and their interaction with humans and the environment. This contact or physical touching between robot and human is subject to special requirements as regards softness and compliance of motions. The goal of humanoids is not to assemble printed circuit boards that are also hard for humans, but also to master soft and energy-optimised movement in different situations of life.

The difference between a machine and a humanoid is its morphology. A human is living and can fulfil several different tasks, which have special requirements in construction, freedom of movement and arrangement of weight. If we assume that the human body is an optimised structure, we have to study the load-bearing skeleton and the load transmission via the muscle-tendon system. Both criteria together form a unit, which cannot be treated separately.

[1] This project was supported by Markus Fischer, TC-D, Corporate Design, FESTO AG & Co. KG

The study of the physiology of the muscle-tendon system [1-4] and its activation by the central nervous system gives us insight into the functions and activities of the human body. Current walking robots are heavyweight, unproportional and unable to accomplish human-like performance. The motor actuators located in the joints increase the masses moved and accordingly the torque as well. The human muscle has a high power-weight ratio and transmits tractive power via a tendon across special parts of bones. There are located on the top or proximal to the centre of rotation. This leads to less torque and the ability to carry out fast movement with respect to energy need.

A closed humanoid robot project in Germany is the development and construction of a two-arm robot called "Zwei-Arm-Roboter" (ZAR5) in German. The fifth prototype has been constructed where two arms each with a five-finger hand has been attached to a rigid spinal column.

The robot is 190 cm tall and the proportions are similar to humans of this size. Attention has been concentrated on its human size, anthropomorphic proportions and functionality of the actuators. The radius of action as well as the velocity of movement is anthropoid. The company FESTO has provided the linear actuators of the fluidic muscles. Tendons of Dynema filaments are used to convey the tractive force to the joints as regards tensile strength, lightweight and little bending radius.

The next section will describe the mechanical body with reference to skeleton, joints and tendons.

2 Mechanical Aspects

The whole body has been designed by AUTOCAD and the date translated to the special Computer Numerical Control (CNC) code and transferred to a 3 axes CNC milling machine. All parts, about 950 not including the purchased parts, have been manufactured from aluminium. Aluminium is lightweight, strong enough and easy to machine.

ZAR5 consist of a base, which can roll, a rigid spinal column, two upper arms, two forearms and two five-finger hands, see in Figure 1.

The mobile base houses the control PC, the electronics, valves for the body actuators and the power supply for the whole robot.

A 5/3-port directional control valve is needed to drive each muscle. Fast relay valves of the company FESTO with a discharge of 100 l/min and a maximum switching time of 2 ms of the type MHE2 are used. Only the valves for the body muscles are located in the base, thus there are 16 valves for 8 body muscles.

The air supply is directly connected to the valve cluster and is partitioned into two separate air tubes, one for the body and one for the hand. This becomes necessary, as there are body muscles, which can be driven with a higher pressure than the small finger muscles. The outgoing air is routed to a common tube and is actually not won back. We presently use two different air supply alternatives. Both alternatives are not really suitable for mobile use. Our in-house compressed air line with 6 bar is used for stationary operation whereas we utilise standard 10 litres 200 bar compressed air bottles encased in a smart aluminium case for 'mobile' use. Current small sized and noiseless air generators cannot produce the required amount of volume flow to fill up the bigger muscles.

To increase the reliability, the power supply is physically split into one for the electronic devices with 5 V and one for the valves with 24 V. We use the switching power supply (SPS) SPS 100PX with an output of 5 V/10 A. The 24 V output of the SPS does not supply the required current start-up peak of the electronic driven valves. A disadvantage of SPS is the break-down of the voltage by overload a special power supply has been assembled for this task and facilitates the delivery of up to 20 A by 24 V.

Figure 1 Photograph of the final version 5 of the humanoid muscle robot torso in action, © Festo AG & C0. KG

The fifth version of the ZAR comprises two hands, the associated arms and the shoulders. Each hand and arm with shoulder constitutes independent units and is steered separately. This basic concept of decentralization by many small 'intelligent' units is found in nature and also has advantages in technical realization. The decentralized control architecture and the associated electronic components are explained in more detailed in section three.

2.1 Five-finger Hand

The hand is the human beings' door to the outside world. The loop of interaction with the environment is that the brain manipulates the information provided by the sense organs, which then are executed by actuators to the extremities. The hand has to accomplish a variety of positions, operations and activities in the life of a human, to survive the rat race. The hand has been optimised to fulfil these manifolds task in the hundred million years of human life. The hand is able to sign, to grasp, to hold and carry, to interact with itself, to dig, to write, to play and a lot more. It is still however lightweight enough to run with a complete runner the 100 m in less than 10 sec. A full-grown human hand weighs approximately 500 g and has a far greater degree of freedom than 16.

The first artificial hand developed and constructed based on the archetype of the human hand was the Waseda Hand (WH-1) in 1964. Since this there have been a multitude of artificial hands, which are more or less anthropomorphic, anthropoid, human-like or humanoid. The academic question regarding humanoid hands, which are not actually humanoid in construction and function, will not be discussed here. The following small survey of artificial hand constructions is not exhaustive.

Many three and four finger hands with more-or-less humanoid proportions have been designed. The Utah/MIT dextrous hand [5, 6] has a four-finger system with 16 DOF and is powered by 32 pneumatic actuators. The actuator pack is placed remote from the robot hand and connected by antagonistic polymeric tendons. The Karlsruhe dextrous hand II [7, 8] can be considered to be a non-anthropomorphic approach. Tendons drive the four-finger autonomous gripper. Other artificial hands are the Stanford-JPL hand [9, 10], the Omni hand [11], the NTU hand [12], the DLR hand [13, 14] with a semi-anthropomorphic design, the cybernetic hand prosthesis by IST-FET [15] and the DIST hand by Genoa Robotics [16-18]. These hand projects do not fulfil the requirements for the number of fingers, joints in the fingers and human-like movements. However, the professional design, control architecture and functionality of a couple of them is convincing.

Several artificial anthropomorphic five-fingered hands have been designed with servomotors, which are built into the fingers, for example, the “Gifu hand” I-III [19-21] has 20 joints with 16 DOF and is equipped with a six-axes force sensor at each fingertip. The Gifu hand is intended to be a prosthetic application for handicapped individuals. The “Robonaut” [22], designed by NASA’s Johnson Space Center and DARPA, is a dexterous five-fingered hand with 14 DOF and a human-scale arm. The forearm houses all fourteen brushless motors and all of the wiring for the hand. The prosthetic hand described in [23, 24] has 24 DOF and is controlled by EMG signals detected from the forearm of a human handicapped individual. A tendon driven adaptive joint mechanism adjusts velocity and torque functions by use of a spring type wire as an elastic guide. The “Blackfingers” hand prosthesis [25, 26] is a five-fingered hand with traditional pneumatic cylinders, which function as linear actuators. The so-called bionic five-fingered hand by FZK (IAI) [27, 28] has 13 DOF and utilises flexible fluid actuators [29]. This fluid actuators approach is the attempt to design muscles similar to those of the human, but which do not have the human-like power-weight ratio. The “Smart Award Hand” from SHADOW [30] has improved this ratio. This artificial robotic five-fingered hand has 24 DOF and is complete driven by air muscles from the company SHADOW. The muscle pack of the hand is located on the forearm and use tendons to power transmission. This design and philosophy of a humanoid hand goes in the same direction as those of ZAR5.

The hand is the most complicated component of the ZAR5. Not only the small limbs and joints of the fingers, but also the guidance of the tendons in human size proportions render the hand the most elaborated part of the project. The hand was assembled separately, tested on a vice and was finally attached to the arm.

The hand has 12 DOF without the wrist. Taking into account the diameter size of the smallest muscle from FESTO, we decided to only attach the flexor muscle to each finger limb and lay on the extensor as the pullback spring. This construction does not constrict the task of grasping, but only active releasing. However, this results in the forearm revolver being reduced in size and mass and, due to this, to a smaller inertia of masses and control effort. A disadvantage of this concurrence is the unnecessary additional expenses of providing tractive force via the small muscles to over-come the resilience of the springs.

All joints of a human hand have been implemented to the greatest possible extent. Each of the four long fingers has three hinge joints. The outer first and middle joint of each finger is coupled because only very few humans can move these joints separately. Consequently, eight muscle actuators are required. All four long fingers are coupled at their roots by a spreading mechanism actuated by one muscle. The fingers fan each other at the same angle around the middle finger, which constitute the fixed base. This artifice simplifies the matter and retains the relation. The different spreading of the fingers is also a challenge for humans. One can observe that the middle finger is fixed on one’s own hand. The thumb has two hinge joints and a saddle joint at the root; therefore only three muscle actuators are required. Altogether, 12 muscle actuators fulfil full functionality of a real human hand. Figure 2 shows the hand of ZAR5.

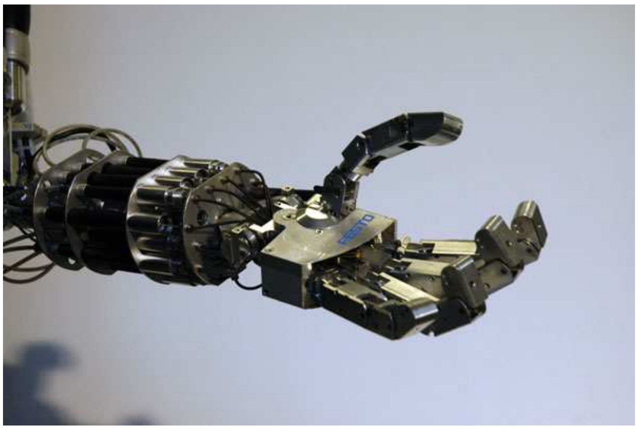

Figure 2 Photograph of the final version 5 of the five-finger hand in action, © F. Bannasch, I. Boblan

The size, weight, morphology and functionality are similar to the human hand and as well the radii of action. The artificial hand can grasp things and hold several poses.

2.2 Fluidic Muscle Actuator

The idea of an inflatable rubber tube to facilitate shortening is not new.

The McKibben muscle actuator [31-34] was developed in the 1950s and 1960s. The deflated rubber tube was not stiff enough to hold the shape itself, which means without an amount of air inside, the muscles kink off and have to firm up additionally.

The company SHADOW attempted another approach. This muscle actuator is also flexible, but is wrapped in a tough plastic weave to hold the cylindrical form. However, an exact deformation across the whole length and diameter and according to this a geometric measurement is not possible.

A large company called FESTO have constructed a fluidic muscle actuator over the last few years using the above-mentioned characteristics [35-38]. This muscle sufficiently meets the requirements of dimensional stability, quantity of shortening and lightweight construction.

A muscle actuator works as a linear actuator and has advantages compared to a hydraulic cylinder and an electric motor with leverage in terms of mass. In addition, the hydraulic cylinder has the problem with a disagreeable leakages and the electric motor, if placed directly at the joint without leverage, with an increase of mass and consequently, with a greater control effort.

The company FESTO officially provides three different sizes of muscle actuators, namely MAS/DMSP-10/20/40. A smaller version, MAS/DMSP-5, is currently being prepared for realise. All types of muscles are used in our robot ZAR5. The number indicates the inside diameter in millimetres. All muscles have the same characteristic, which is the shortening contraction to the acting force dependent on the level of compressed air inside the muscle. This relationship is shown in the following Figure 3.

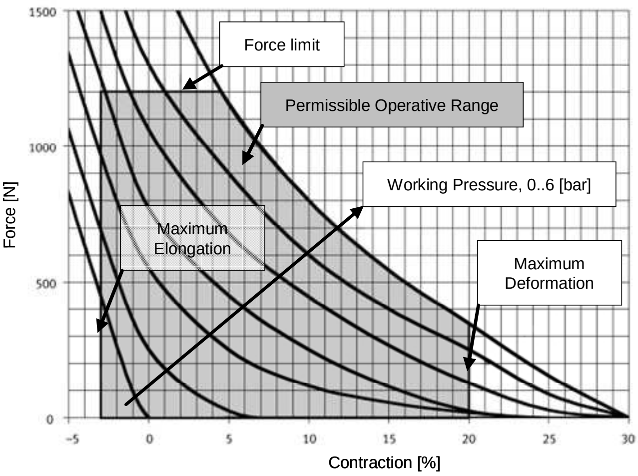

Figure 3 Relationship of the tractive force to contraction rate by a given working air pressure of the MAS/DMSP-20

This non-linear interrelationship is commonly depicted as force F in Newton over contraction Δl in percent with supplied air pair in bars as constant parameter. The greater the affected force by a constant air pressure, the smaller the shortening referred to as base length L_0 of the muscle rubber tube. Moreover, the higher the air pressure by a constant force, the greater the shortening.

3 Electronics and Control Architecture

The electronic components, the communication to the controlled PC together with the architecture to manage and control tasks which is what defines when a machine is a robot and is the counterpart to the human brain and the central nervous system. Engineers till date have not been able to reproduce this data flow and communication network in vitro. The task will be to assemble, place and manage electronic parts in the same way as to achieve results similar to that of the human. Many small activities and reactions are not controlled by the brain, but rather initiated by the spinal cord or local reflexes. The advantage of this is faster reaction time; specialized distributed units can be used as a paradigm to design decentralized control architecture. This approach applied to a technical system is tolerant of failure, enables short distances in the sensor-control-actuator loop and provides for command structure and control hierarchy.

The robot ZAR5 is divided into two times two units completely separately assembled and controlled one for the five-finger hand and one for the arm and shoulder both for each side. Both units have identical circuit devices and functional range. Each functional unit consists of two communication directions and can be addressed both separately and independent of each other. The differences lie in the amount of driven outputs, the physical subdivision of input-output channels and the user-defined software of the controller. A diagram of the structural components and communication channels are shown below in Figure 4.

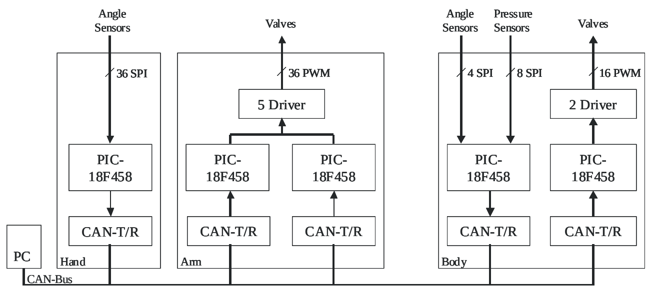

Figure 4 Schematic plan of the connections of the hand ("Hand"/"Arm") and arm ("Body") electronic devices

The body electronics for reading sensors and driving the valve-muscle actuators are located in the base and is arranged on one printed circuit board.

The hand electronics are separated into a sensor input board and an actuator output board to drive the muscle valves. The hand electronics, located on the upper side of the palm, process the data signals from each measured finger joint. The associated output board is placed near to the upper arm valve block on the shoulder.

The angle sensor uses a magnet, placed on the distal part of the joint, which rotates closely below a sensitive array. This array is implemented as integrated circuit to detects the changing magnetic field and works as a magneto-resistive sensor. This non-linear relation compensates for temperature and is linearized at the sensor spot. The communication protocol Serial Peripheral Interface (SPI) from each angle transmitter is used to transmit the digitalized angle sensor data directly to the PIC microcontroller 18F458 from the company MICROSHIP. The SPI interface is used as it requires less effort to wire, has a high data rate and as it provides the possibility of connecting to the controller. The three-wire-bus consist of two data and one clock signal and works in the master-slave-mode.

The two PIC 18F458 controllers, each concerned with one signal path, communicate via the Controller Area Network (CAN) bus and shares the effort of data processing, executing of control loop and generating of Pulse Width Modulation (PWM) signals. The CAN transceiver/receiver allocates the signal level to the physical bus. Driver devices, each of which have eight outputs, realize the 24 V output level for the electronic driven valves and must provide up to 1 A inrush current per valve. To drive each valve, electronics are needed on the one hand to supply current demand and, on the other hand, to enable the height switching time of the PWM output.

The strict separation of different components and data directions enables speedier troubleshooting and is a first step towards of decentralization. The distribution of responsibilities and the break down of information handling reduced data activities on the bus and the complexity of the units. The fast response time of a unit in a control loop in case of emergency cannot be affected by a fewer crucial task of monitoring or finger play. The remote unit receives a command from the control PC or from another unit via CAN-bus and decides about which operations to be done. Without any errors, the unit will initiate the appropriated control loop to reach the demanded goal angle. This stand-alone execution can be interrupted by the control PC or by an exceeded sensor limit value. The CAN-bus only serves as asynchronous communication channel of control and information messages not for the synchronous control loop between sensor, controller and actuator. The transmission of the entire control loop data via CAN-bus leads to an exceeding of the data rate specification of CAN of 1 Mbit/sec at the latest by triggering of the second arm. However, there is a possibility to use the CAN-bus which is carried out between the palm and shoulder board for the hand control loop. The next generation of ZAR will prevent this issue.

4 Conclusion

It is far more difficult to design a practicable human-like robot than it would at first seem to be. Being constrained to human-like proportions increases the manufacturing effort, which is compounded by being able to find practicable analogies and solutions for geometrical and functional interrelationships in human morphology and physiology. This has to lead to a completely new process of thought. The science of Bionik aims at analysing the methods behind the processes and to translate them into a practicable technical solution; this helps to construct machines, which are similar to the model in nature, particular as regards excellence in shape and function.

This manuscript introduces the humanoid robot ZAR5. The mechanical design and development process is explained and constraints and limitations pointed out. A practicable artificial fluidic muscle is briefly proposed and the fundamental correlation of length, force and pressure introduced. Descriptions to the electronics and control architecture close the demonstration.

The humanoid muscle robot torso is fully functional and able to perform.

5 Acknowledgement

The company FESTO AG & Co. KG which supports the work on the various versions of the muscle robot ZAR.

6 Literature

[1] Fenn, W.O. and B.S. Marsh, Muscular force at different speeds of shortening. Journal of physiology, 1935. 85(3): p. 277-298.

[2] Gordon, A.M., A.F. Huxley, and F.J. Julian, The variation in isometric tension with sar-comere length in vertebrate muscle fibres. Journal of Physiology, 1966. 184: p. 170-192.

[3] Carlson, F.D. and D.R. Wilkie, Muscle Physiology. 1974: Prentice-Hall, Inc.

[4] Huxley, A.F., Muscular Contraction. Journal of Physiology (London), 1974. 243: p. 1-43.

[5] Jacobsen, S.C. and e. al., The Utah/MIT dexterous hand:Work in progress. Int. J. Robot. Res., 1984. 3(4): p. 21-50.

[6] Jacobsen, S.C., et al., Design of the Utah/MIT Dextrous Hand. Proceedings IEEE Int. Conf. on Robotics and Automation, USA, 1986: p. 1520-1532.

[7] Fischer, T. and H. Woern, Structure of a robot system: Karlsruhe dextrous hand II. Proc. of Mediterranean Conf. on Control and Systems, 1998.

[8] Osswald, D. and H. Wörn, Mechanical System and Control System of a Dexterous Robot Hand. Proceedings of the IEEE-RAS International Conference on Humanoid Robots, 2001: p. 8.

[9] Salisbury, J.K., Articulated Hands: Force Control and Kinematics Issues, in Stanford University. 1982: Stanford.

[10] Salisbury, J.K., Design and Control of an Articulated Hand. Int. Symposium on Design and Synthesis, Tokio, 1984.

[11] Rosheim, M., Robot Evolution. New York: Wiley, 1994: p. 216-224.

[12] Lin, L.R. and H.P. Huang, “Integrating fuzzy control of the dexterous National Taiwan University (NTU) hand. IEEE/ASME Trans. Mechatron, 1996. 1: p. 216-229.

[13] Butterfass, J., et al., DLR’s Multisensory Articulated Hand Part I: Hard- and Software Architecture. IEEE International Conference on Robotics and Automation, 1998: p. 2081-2086.

[14] Butterfass, J., et al., DLR-Hand II: Next Generation of Dextrous Robot Hand. Proc. IEEE Conf. on Robotics and Automation, Seoul, Korea, 2001: p. 109-114.

[15] Dario, P., et al., On the development of a cybernetic hand prosthesis.

[16] Bernieri, S., et al., The DIST-Hand Robot. IROS '97 Conf. Video Proceedings, Grenoble, France, 1997.

[17] Caffaz, A. and G. Cannata, The Design and Development of the DIST-Hand Dextrous Gripper. Proc. IEEE Int. Conf. on Robotics and Automation, Leuven, Belgium, 1998: p. 2075-2080.

[18] Caffaz, A., et al., The DIST-Hand, an Anthropomorphic, Fully Sensorized Dexterous Gripper. IEEE Humanoids 2000 Boston, MIT, USA, 2000.

[19] Kawasaki, H. and T. Komatsu, Mechanism design of anthropomorphic robot hand: Gifu hand I. J. Robot. Mechatron., 1999. 11(4): p. 269-273.

[20] Kawasaki, H., T. Komatsu, and K. Uchiyama, Dexterous Anthropomorphic Robot Hand With Distributed Tactile Sensor: Gifu Hand II. IEEE/ASME TRANSACTIONS ON MECHATRONICS, 2002. 7(3): p. 296-303.

[21] Mouri, T., et al., Anthropomorphic Robot Hand: Gifu Hand III. ICCA, Muju Resort, Jeon-buk, Korea, 2002: p. 6.

[22] Lovchik, C.S. and M.A. Diftler, The robonaut hand: A dextrous robot hand for space. Proc. IEEE Conf. on Robotics and Automation, 1999: p. 907-912.

[23] Hirose, S. and S. Ma, Coupled tendon-driven multijoint manipulator. Proceedings of IEEE International Conference on Robotics & Automation, 1991: p. 1268-1275.

[24] Ishikawa, Y., et al., Development of Robot Hands with an Adjustable Power Transmitting Mechanism. Intelligent Engineering Systems Through Neural Networks, ASME Press, 2000. 10: p. 631-636.

[25] Folgheraiter, M., et al., Blackfingers a Sophisticated Hand Prothesis. p. 4.

[26] Folgheraiter, M. and G. Gini, Blackfingers an artificial hand that copies human hand in structure, size, and function. Proc. IEEE Humanoids 2000, MIT, 2000: p. 4.

[27] Schulz, S., C. Pylatiuk, and G. Bretthauer, A new ultralight anthropomorphic hand. Pro-ceedings of the 2001 IEEE International Conference on Robotics & Automation Seoul, Korea, 2001: p. 2437-2441.

[28] Pylatiuk, C. and S. Schulz, Neuentwicklung einer Prothesenhand. Prothetik, 2002. 8: p. 4.

[29] Pylatiuk, C. and S. Schulz, Entwicklung flexibler Fluidaktoren und ihre Anwendung in der Medizintechnik. Med. Orth. Tech., 2000. 120: p. 186-189.

[30] Design of a Dextrous Hand for advanced CLAWAR applications. 2003, Shadow Robot Company: 251 Liverpool Road London ENGLAND.

[31] Schulte, H.F.J., The characteristics of the McKibben artificial muscle. The application of external power in prosthetics and orthotics, National Academy of Science-National Research Council, Washington D.C., 1961.

[32] Chou, C.-P. and B. Hannaford, Static and Dynamic Characteristics of McKibben Pneumatic Artificial Muscles, in IEEE. 1994, Department of Electrical Engineering, FT-10, University of Washington: Seattle, Washington 98195. p. 281-286.

[33] Colbrunn, R.W., Master of Science, in Department of Mechanical and Aerospace Engineering. 2000, Case Western Reserve University. p. 141.

[34] Tsagarakis, N. and D.G. Caldwell, Improved Modelling and Assessment of pneumatic Muscle Actuator. Proceedings of the 2000 IEEE International Conference on Robotics & Automation, San Francisco, CA, 2000: p. 3641-3646.

[35] Hildebrandt, A., at al., A Flatness Based Design of Tracking Control of Pneumatic Muscle Actuators, The Seventh International Conference on Control, Automation, Robotics and Vision - ICARCV 2002, Singapore in December 2-5, 2002

[36] Hildebrandt, A., et al., A cascaded tracking control concept for pneumatic muscle actuators, European Control Conference 2003 (ECC03), Cambridge UK, (CD-Rom), 2003.

[37] Neumann, R.; et al., Ein Positionierantrieb mit hoher Kraft: Positions- und Druckregelung eines künstlichen pneumatischen Muskels. Beitrag zum 4. Internationalen Fluidtechnischen Kolloquium, Dresden, March 25th-26th, 2004, Pages 12

[38] Boblan, I., et al., A Human-like Robot Hand and Arm with Fluidic Muscles: Modelling of a Muscle Driven Joint with an Antagonistic Setup, 3rd Int. Symposium on Adaptive Motion in Animals and Machines, Technische Universität Ilmenau, Germany, September 25th-30th, 2005, Pages 7, ISBN 3-938843-03-9