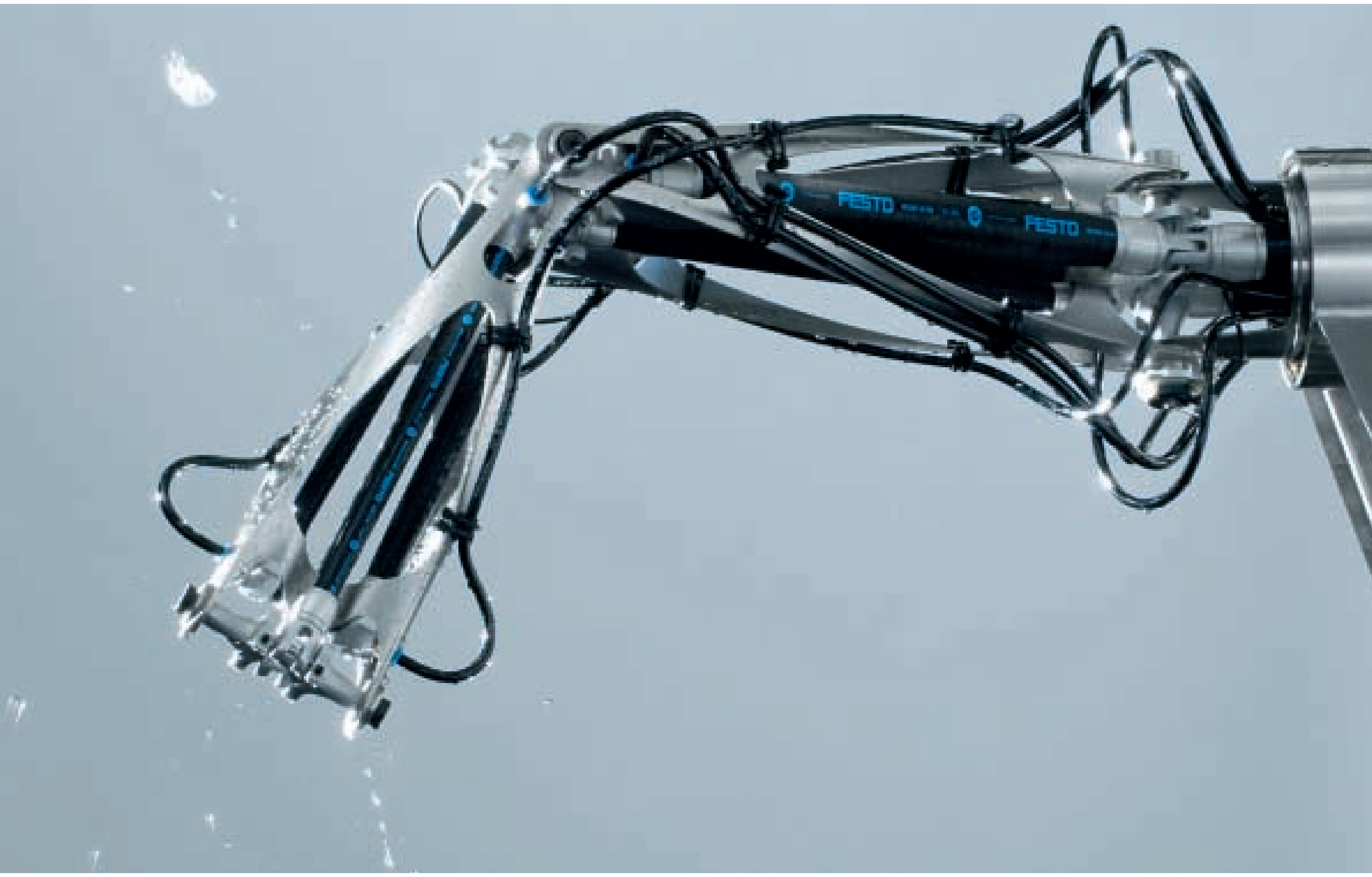
AirArm



AirArm catches
drops of water

Info

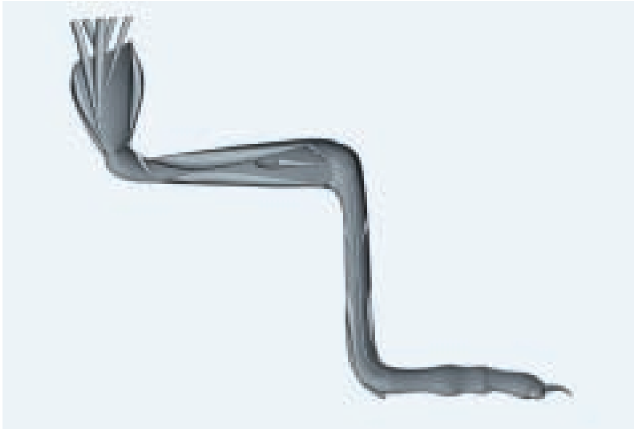
Biologically inspired by analyses of lobsters' and grasshoppers' legs and of human pointing gestures, a two-segmented arm with an external skeleton has been developed with movement patterns similar to those of a human. Powered by pneumatic muscles, "AirArm" catches drops of water.

A scientific functional analysis of the human arm identified numerous opportunities for technical realisation. The technical purpose of the "arm" is seen as that of reaching as many remote points as possible within a hemispherical operating range from a specified point in space.

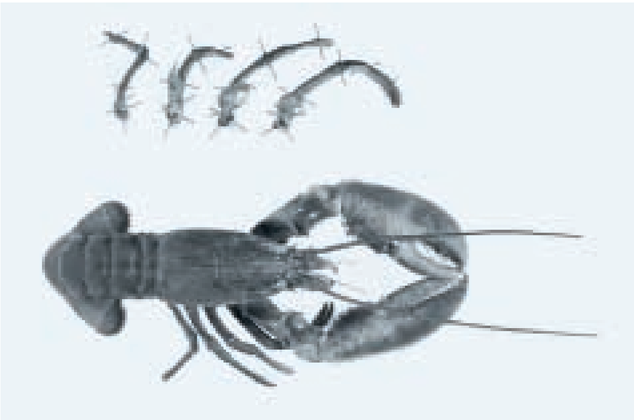
As prerequisites for various possible approaches under the heading of "smart mechanics", the following categories were outlined:

- lightweight design
- flexibility
- resilience
- reduced complexity
- robustness
- adaptive control

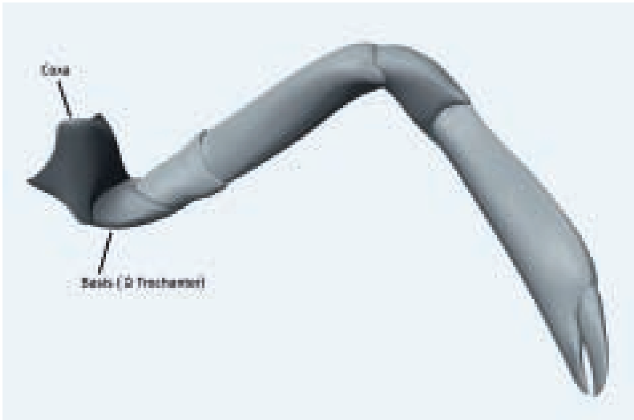
Longitudinal section of grasshopper's leg with internal muscles (specimen)



Flexor and extensor muscles of the grasshopper's leg (computer image)



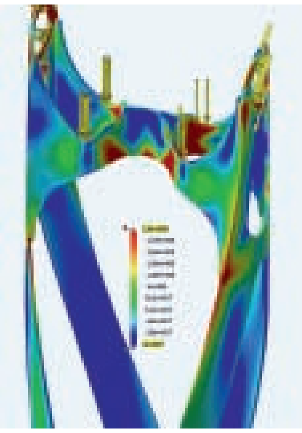
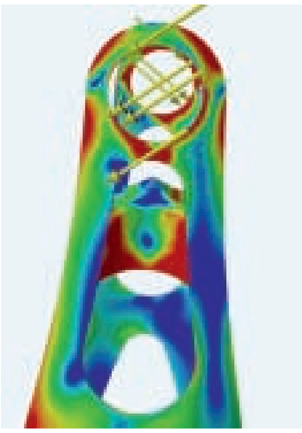
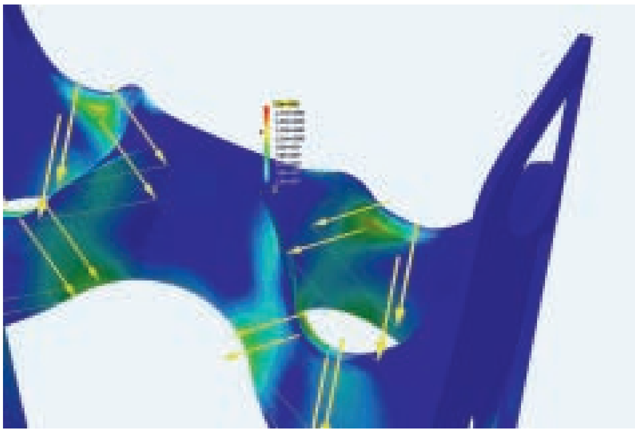
Lobster's leg (specimen) with angularly displaced joints



Lobster's leg (computer image)

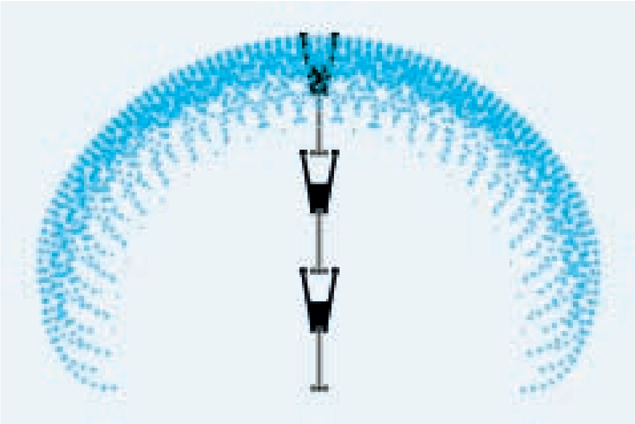
In designing the joints, inspiration was derived from examples found in living nature. Via the joints of the grasshopper’s leg located close to the body (in particular the coxa trochanter joint), the search led to the lobster’s leg with its angularly displaced axes of motion. A two-segmented flexing system with muscles operating in contrary motion was chosen as the general principle for technical realisation. By analogy with the natural model, the design was to be kept as simple as possible, and the principles and structures were to be duplicated at various levels; this is known as selfsimilarity.

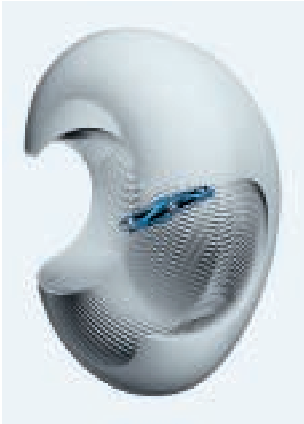


To ensure both lightness and robustness, triangulation of the arm modules was executed by analogy with the exterior skeleton of a grasshopper's leg. By crossing over the joint axes of the lobster's leg and adapting the segment lengths, a favourable compromise was achieved between simplicity and versatility for the reaching movements within the hemispherical range of operation. The pneumatic muscles as an antagonistic mechanism allow a high degree of yielding ability in combination with minimal expenditure of energy to remain stationary in a specified position.

Two-dimensional design and contour sketches were initially drawn up for all the functional components required for technical implementation. The three-dimensional realisation was effected using CAID, with verification of the datasets in design programs. The datasets generated by this means served as a basis for production of the functional components by 3D laser processing and multi-axis CNC milling. In designing AirArm, care had to be taken to ensure that the various functional components could be readily produced from normal metal blanks. To reduce weight, the raw components were therefore lathed on both sides down to the minimum necessary thickness, and the three-dimensional contours were added by laser; reinforcement elements were laser-welded to the basic corpus. In view of AirArm's operation with the medium of water, it was manufactured in stainless steel. As bearings, standard production components were used that effected the best compromise between weight and costs. Here too, the conflict of interests between lightweight design and robustness placed high demands on the design of the functional components. By means of intricate rigidity (FEM) analyses, an optimised component shape and load capacity were realised, and sufficient safety tolerance ensured.

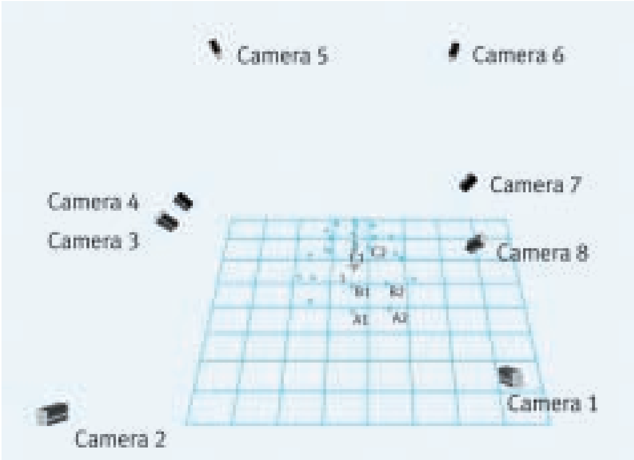




To attain optimum kinetics for the arm system, the standard muscles of Festo were modified in the following points:
Specially shortened fork joints were designed, and the opposed bearings were devised as integrated press connections that ensure compressed air supply, self-centring and the required degree of rotation.

The dynamics of the arm system and the patterns of motion within its range of operation were already visualised by means of motion simulation and computer animation prior to production of the functional components, so that the kinetic characteristics could be analysed and critical system conditions identified at an early stage.

Experimental setup. Arm and target of the reaching movement are marked by reflective balls.



Rat, reaching (x-ray image)

Computer animation

The initial biological inspiration for AirArm was provided by the legs of the grasshopper and the lobster – i.e. legs with internal muscles and an exoskeleton, as are typical of arthropods. However, since AirArm was to combine the structure of an arthropodic leg with the operating radius of the human arm, the axes of rotation and range of motion of the leg joints first had to be determined. It was found that unlike in the case of vertebrates, each successive joint of the arthropodic leg flexed at right angles to the preceding one. The central rotational movement of the arthropodic leg is the sum of the scope of movement of the four joints closest to the body. This yields an overall rotation of at least 220°. By contrast, the large scope of operation of the human arm is achieved through a high degree of manoeuvrability in the shoulder joint and muscle-assisted flexibility of the shoulder blade.

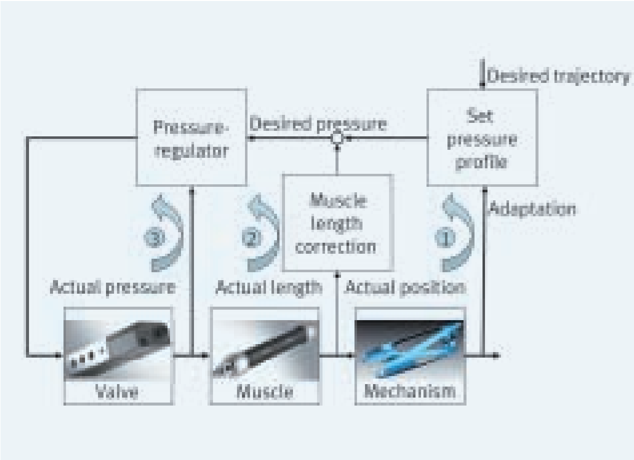
Selected joint angles of a lobster's leg

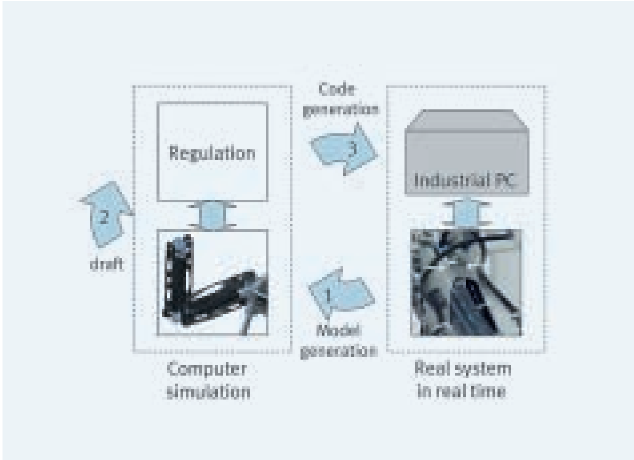
		Joint axis	Range of motion
Thorax	Coxa	to the centre/to the side	approx. 45°
Coxa	Trochanter	to the front/to the rear	approx. 85°

Proportion of selected lobster leg segments to total leg length

Coxa	1
Trochanter	1

The processes of reaching and grasping in mammals were investigated with rats, by means of a high-resolution x-ray camera with up to 1,000 images per second in two planes. This procedure highlighted the significance of the shoulder blade in executing these movements. Since this method is precluded with human subjects, surface measurements of the arm were used to determine the shoulder blade's role in human reaching movements (motion capture). The results largely corresponded to those determined in the x-ray analysis of rats.





An anthropomorphic, i.e. human-oriented, approach was not adopted in the design of AirArm; rather, the principle of "rotation effected close to the body" was transferred to the use of linear drives (anthropofunctionality). After all, seeking inspiration from nature does not mean directly copying human arm movements (referred to as "biomimikry"), but entails the technical adaptation of human movement patterns, in this case with a lever system based on different lengths, proportions and modes of actuation. Reaching for points within the hemisphere was interpreted as the index finger "reaching" to points on a spherical surface. The movements of the human arm were registered with an infrared-aided movement analysis system. In evaluating the lines of movement, patterns of joint flexing were observed that could be summarised in the form of (apparently) simple rules. The structural solutions produced in the process of human evolution need not be copied; the significant requirement is that the appropriate lengths and forces are made available by technical means. It is not necessary to imitate the human shoulder joint.

In analysing the pointing movements, the coordinates of the reference points – marked in the form of reflective spots – and of the targets are registered by means of an infrared camera system generating up to 1,000 images per second. This tracking of coordinates as a function of time provides the basis of motion analysis.

The pneumatic muscles used as a drive mechanism have a very favourable ratio between the high mechanical forces attainable and their low weight. The advantages of AirArm thus come to the fore above all where rapid dynamic movement is required. On the other hand, the pneumatic muscles are also highly elastic, and the relations between their contraction, their pneumatic pressure and the forces produced are non-linear. As with its biological model, the technical system must also learn to deal with this situation – this is the task of AirArm's control unit!

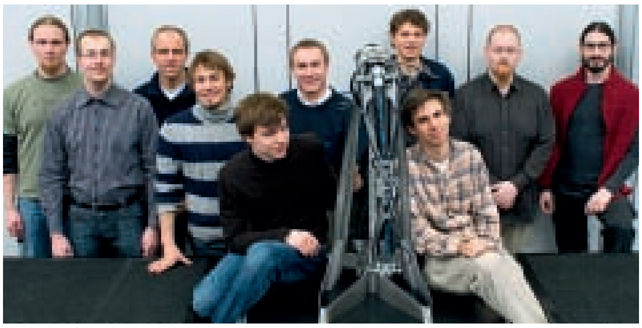
AirArm is controlled by means of three nested feedback loops (see diagram):

1. The desired motion of the arm from point A to point B is converted into reference pressure progressions for all pneumatic muscles. The data required for this calculation was initially provided by a mathematical model of AirArm. On conclusion of a movement, an assessment is made as to whether the arm has in fact executed the movement in the desired manner. For this purpose, the angles of articulation are constantly measured; in case of deviation, the pressure trajectories are modified accordingly. AirArm thereby "learns" to constantly adapt its movements and to react to changes in its surroundings.

2. This loop monitors the muscle lengths. Unlike customary positional control circuits, it serves merely to correct the pressure progression; this prevents vibration in the dynamic movement.

3. The pressure regulator ensures stable pressures in the pneumatic muscles by comparing the actual pressure at each valve outlet with the calculated reference pressure and addressing the valves as required.

The entire control system is designed on the basis of a model: the mathematical model of AirArm is first devised on a computer, on which the control system is then drafted and optimised. This system is then transferred via automatic code generation to an industrial PC, which controls AirArm on a real-time basis (see diagram).



Technical data

Upper segment (upper arm):	
Segment length	389 mm
Diameter	123 mm
Structural weight	1,022 g
Lower segment (forearm):	
Segment length	311 mm
Diameter	104 mm
Structural weight	763 g
Scope of operation:	
Hemisphere, radius	750 mm
Festo components:	
Fluidic Muscle	DMSP 10
Fluidic Muscle	DMSP 20
Fluidic Muscle	DMSP 40
Proportional directional-control valve	MPYE-5-1/8LF-10-B
Proportional directional-control valve	MPYE-5-1/8HF-10-B
Precision pressure regulation valves	MS6-LRPB
Pressure sensor	SDET-22T-D10-G14-U-M12
Pressure sensor	SDET-22T-D16-G14-U-M12
Pressure sensor	SDE1 with display
Pressure booster	DPA-100-16
Compressed air reservoir	VZS-20-B
Compressed air reservoir	0.4l CRVZS-0.4
Filter control valve	MS6-LFR
24 V DC 5 A mains adapter	SVG-1/230VAC-24VDC-5A
24 V DC 10 A mains adapter	SVG-1/230VAC-24VDC-10A

Project partners

Project initiator:
Dr. Wilfried Stoll, Chairman of the Supervisory Board, Festo AG

University of Industrial Design and Art, Linz
Faculty of Industrial Design/scionic®

Univ.Prof. Dipl.-Ing. Axel Thallemer, Head of Faculty
Univ.Prof. Dipl.-Ing. Martin Danzer, Head of CAID
Sebastian Bauschke
Christoph Brandner
Dominik Dienstuber
Martin Frittajon
Michael Holzer
Michael Kogelnik
Dieter Lang
Michael Paar
Bernhard Rogler
Mathias Roher
Marinus Schmid
Andreas Schnegg
Peter Zehetbauer
Emanuel Zeindlinger

Technical University of Ilmenau
Faculty of Mechanical Engineering
Institute of Microsystems Technology, Mechatronics and Mechanics
Interfaculty Institute of Micro- and Nanotechnologies
Department of Biomechatronics

Univ.-Prof. Dipl.-Ing. Dr. med. (habil.) Hartmut Witte
Specialist in anatomy, Head of Faculty
Dipl.-Ing. Tobias Schmidt
Dipl.-Ing. Lars Lehmann

Technical University of Ilmenau
Faculty of Computer Science Technology and Automation
Institute for Automation and Systems Engineering
Department of Systems Analysis

Univ.Prof. Dr.-Ing. (habil.) Christoph Ament, Head of Faculty
Dr. Mike Eichhorn

Friedrich Schiller University of Jena
Institute of Systematic Zoology and Evolutionary Biology
with Phyletic Museum

Prof. Dr. Martin S. Fischer, Director
Jonas Lauströer

Fotos: Walter Fogel, Angelbachtal, Germany

Festo AG & Co. KG

Corporate Design
Rechbergstraße 3
73770 Denkendorf
Germany
www.festo.com/de/bionic
Telefon +49/7 11/347-38 80
Telefax +49/7 11/347-38 99
fish@de.festo.com

52974 EN