New Compliant Mc-Kibben Actuator Driven by Pneumatic Actuators as a Hexapod Platform in Robotic Applications

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Abstract
This paper presents the design and implementation of a parallel-kinematic hexapod tool driven by pneumatic actuators. It consists of six discrete linear actuators, each of which is assembled as an antagonistic setup of McKibben pneumatic muscles with pressure and position sensors. Thanks to the antagonistic principle of the units together with the inherently nonlinear behaviour of Mc-Kibben actuators, the stiffness of the hexapod can be adjusted and thus selected within a wide range. As a whole, the hexapod can be considered as a simple adjustable passive damping and uncoupling unit that can be mounted at the TCP of a serial industrial robot, for example. As second application, the unit can be used as a combined sensor/actor device with the ability to give a force feedback to the user. The unit can therefore be used as a stand-alone device where the forces applied to the hexapod's TCP can be measured and the TCP's position can be altered corresponding to the desired force of the respective application. The main targeted area of application is warm compact-forging assisted by industrial robots. This process is characterized by high impulse forces. In case of a conventional robot holding the workpiece in-process, these force impulses are lead from the workpiece through the endeffector and the gears into the robot's electrical drives. Since the stiff mechanical structure of the gears is not well-designed for high impulse forces, today the parts have to be released during the process. Introducing a lightweight compliant structure designed as a hexapod attached to the endeffektor, force impulses can be considerably attenuated and robot-based holding and manipulating parts during forging becomes possible. This tool has been realized with the help of compliant pneumatic actuators.

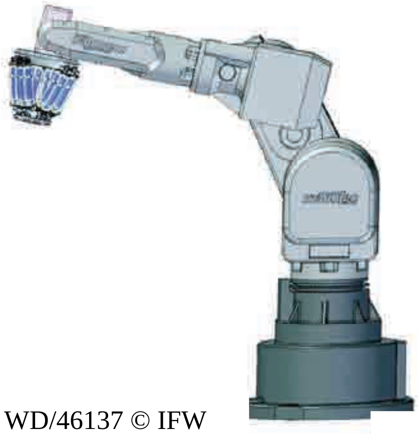
Keywords: Pneumatic Actuator, Mc-Kibben Principle, Compliant Fluidic Muscle

I. Introduction

Due to the harsh industrial environment found in forging processes, these do still show a considerable lack of automation compared to other manufacturing processes. The study of the presented hexapod platform has been motivated by the perspective of a solution that makes handling of forging parts accessible to robots, even during the process. Thus, a primary concern of the associated and BMBF-funded research project "koSePro" is the design and development of a compliant adaptive robotic hexapod for industrial applications. The system will be used in applications such as compact forging processes. In this case, the handling of the workpiece will be based on a serial industrial robot. General properties of such a robot are a high structural stiffness and the usage of self-locking drives and gears with very high gear transmission ratios.
Here, the pneumatic hexapod comes into play: the targeted forging process poses several demands on the design of the combined hybrid system. The primary challenge is to significantly attenuate the high force impulses in order to protect the robot. As a solution, the developed hexapod structure will satisfy these requirements through:
a.) Mechanical filtering of external dynamic forces before entering the robot's structure by employing fluidic muscles
b.) Active control and override of the tool's dynamic properties in order to compensate static forces and to increase the precision
c.) Immunity to high process forces and impulses of the hexapod structure itself
Thanks to the sensory capability of the hexapod, the unit can be used as "active sensor". Regarding the internal states of the unit like the pressure in the agonist and antagonist combined with position of the unit, a model-based procedure allows to estimate external loads and forces. Combined with the actuation capability, the system may be used as a force feedback "Human Machine Interface" with six degrees of freedom.
Within this paper, at first the general design of the unit is introduced. The control strategies of the antagonistic pneumatic actuators for a particular linear unit are described together with experimental results and performance measurements. The paper concludes with the results and an outlook into future investigations.

II. Design

The hybrid system consisting of the serial robot and the hexapod is shown in Figure 1 [9]. Figure 2 presents a possible setup to use the compliant hexapod robot as Human Machine Interface (HMI) in order to command a serial industrial robot in a master-slave setup.



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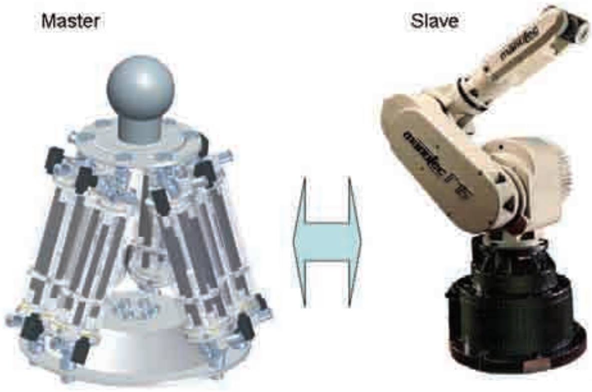

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Fig. 1: *The hybrid system with a serial robot and the hexapod (damping and decoupling usage)*

Fig. 2: *The hexapod as Force Feedback "Human Machine Interface" (sensing and Feedback device)*

The compliant robotic hand is designed as a parallel kinematic platform (see Figure 3) [7]. With the approach taken it becomes possible to adjust the position and the stiffness in six degrees of freedom.
The detailed geometric construction of the hexapod has been carried out with use of finite element methods. A geometrical verification of the design has been accomplished by calculating the inverse kinematics using Matlab™ and additionally with a multi-body simulation [8] of the actuator in MSC.ADAMS™. After specifying the general layout and dimensions of the hexapod structure, the linear actuators have been designed. For the actuation of the endeffector, Mc-Kibben actuators (also known as pneumatic muscles or fluidic muscles, see Figure 5 right) have been chosen. These lightweight actuators consist of a pressure-tight rubber tube wrapped by a grid of high-strength fibers. If internal pressure is applied, the tube expands in radial direction, thus creating a tensile force and a contraction motion in the muscle's longitudinal direction.

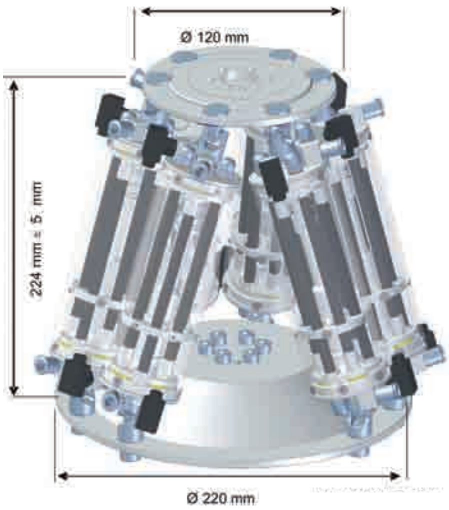

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Fig. 3: *The design of the hexapod platform with compliant and pneumatic Mc-Kibben actuators*

Fig. 4: *Photo of the hexapod platform with compliant and pneumatic Mc-Kibben actuators*

The muscles used in this research project are manufactured by FESTO. They show a strongly non-linear behaviour concerning the actual force depending on the internal pressure and contraction (see plot in Figure 5 left). In general, the tensile force reaches its maximum at the start of the inflation and then decreases as a function of the contraction. More interesting, the stiffness which corresponds to the gradient of the characteristic curve of the muscles is apparently adjustable by changing the pressure.

Since pneumatic muscles can only apply tensile forces, the design of the linear actuators is taking its cue from the principle of human muscles. By interaction of an agonistic and an antagonistic muscle, forces in both linear directions can be provided. In order to deliver high forces and also high stiffness, the design of the single actuator includes three parallel agonistic and three parallel antagonistic muscles. Figure 6 shows a single actuator of the robotic hand.

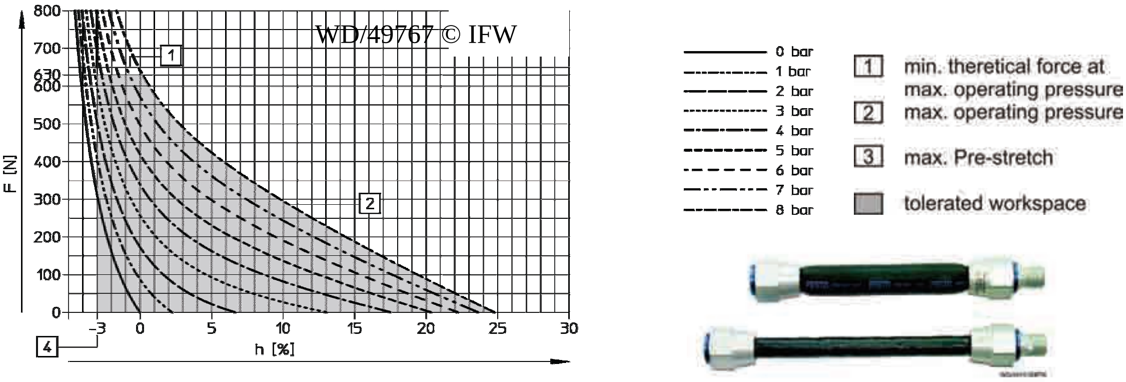
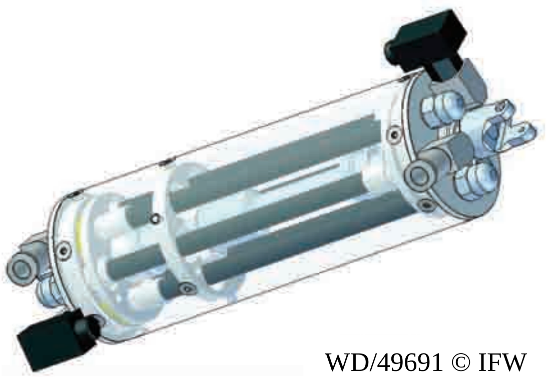


Fig. 5: Tensile force as a function of pressure and contraction and Pneumatic muscles for compliant applications (source: Festo[6])

There are pressure and position sensors directly integrated into the actuator (see Fig. 7). This must be considered already in the design stage to leave enough space inside the actuator and hexapod structure. Thus, a precise closed-loop control of the muscle’s pressure and position is facilitated.



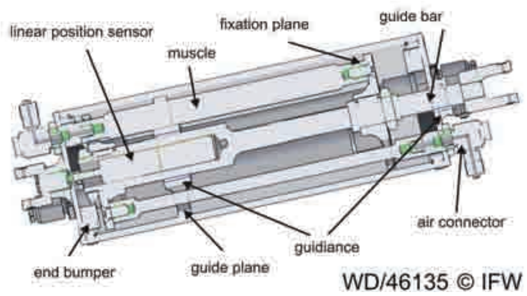


***Fig. 6:** CAD-model of a single hexapod actuator*

***Fig. 7:** Cross section view of a single hexapod actuator*

Pressure sensing is located at the inlet and outlet openings of the muscles as shown in Figure 6. As the sensor type, sensors with integrated amplifiers from Keyence are used. The current position of the actuator’s shaft is determined by a conductive plastic potentiometer, which measures the relative position of the shaft to the body of the single actuator.

III. Control

The schematic of a single actuator’s control loop is presented in Figure 8 [5]. The outputs of the controller are voltages for two proportional valves, one for each group of muscles. The primary objective of the control system is to move each actuator into a defined position [2]. Hence, it contains a superordinate position control [3][4]. Another objective is to adjust the stiffness of the actuator. Therefore, a pre-load force is being calculated according to the actual position of the actuator and a nominal stiffness based on an analytical model of the pneumatic muscles. The pre-load force and the output of the PID-position control provide the inputs of a model-based pilot control for the internal pressure ($p=f(F,x)$). Subsequently, a PID-control of the pressure is part of the control system. To eliminate external forces originating in the application of a forging process, a feedback-controller is also implemented into the controller. [9]
With this design it is possible to measure the external forces indirectly by using the pressure and position signal. Furthermore, it becomes possible to calculate the external forces with use of the available sensor data supported

by the analytical model of the muscles. It is however not possible to measure the force directly. The pilot control for pressure, the calculation of the pre-load force and the force-feedback are based on an analytical model of the correlation of contractile force, internal pressure and contraction of the pneumatic muscles.

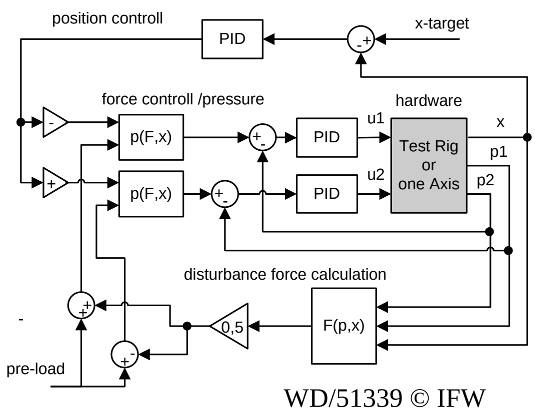


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Fig. 8: *Schematic of the motion control*

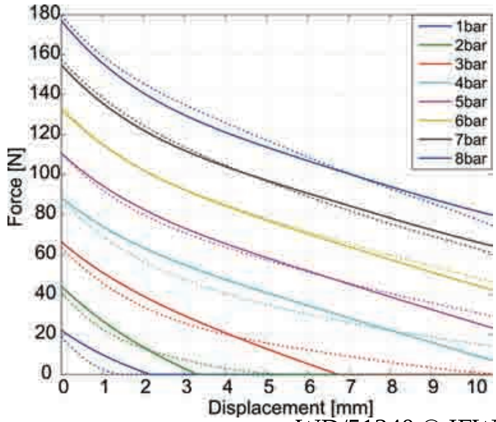

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Fig. 9: *Tensile force as a function of pressure and contraction (… measured force, - modelled force)*

Two different analytical models of the muscles are developed by using a least square fit. This is based on a physical model of the Mc-Kibben actuators developed by Cho and Hannaford [1] and experimental data quantified at the test-rig at IFW. A first modeling approach designed to calculate the tensile force has been a degree 13 polynomial for the pressure and a degree 4 polynomial representing the contraction. This approach is characterized by high accuracy but also by high demands on numerical precision. Figure 9 shows the results of the simplified model. [8] A second simplified model has been developed for an implementation into the control loop using linear functions that can be handled with the limited storage space and computing power of a microcontroller.

To further examine the expected system behaviour, multi-body simulations have been carried out. Co-simulations of multi-body simulation along with technical computing software have facilitated the development and analysis of the complete system and have proven to be less time-consuming and less strain on materials than testing the physical prototype. Furthermore, it has been possible to test and improve the system’s control in quite an early stage of development. By co-simulation of the analytical models and the control system with Matlab/Simulink on the one hand and multi-body simulation using MSC.ADAMS on the other hand, the full mechatronic system of the test-rig, corresponding to the six single actuators and the hexapod structure, has been modeled [8]. With this method an optimal control layout and parameter configuration has been identified. This has then been implemented into the microcontroller code of the axes’ controllers.

Each of the linear actuators of the hexapod features a dedicated axis controller based on an ATMEL ATMEGA16 microcontroller. These six axis controllers are connected via I²C and communicate with a master controller of the same type as the axis controllers themselves. The master controller offers three different ways of operation. At first, it provides a function to connect to an axis controller and individually set the position and the desired stiffness. The second function enables the master controller to communicate with all six axis controllers and to assign position and stiffness based on preset values dependent on the input of tree digital input channels, which results in $2^3 = 8$ different pairs of position and stiffness. The third mode of operation provides a communication interface to an external PC that can calculate the direct and inverse kinematics of the hexapod. In this mode, a haptic interaction can take place.

To bring the system closer to real-world applications, the transformation from the laboratory Matlab-based control system to the ATMEGA16 C-Code has been accomplished. Each axis controller is running at 1kHz and drives two valves (Festo MPYE5) while in same time reading the two pressure signals and the position signal of the axis system. The communication between the master and the six slaves is realized based on an I²C bus running at a speed of 200Hz. Current limitations concerning haptic interaction do especially arise from the communication with the host PC as the kinematic calculator and more specifically from the RS232 serial interface used with 50 Hz. Future improvements may deal with the axis communication level. A faster hardware interface such as CAN allows quicker communication between host, master and slaves and could considerably boost the overall system’s performance.

IV. Extension towards a haptic feedback device

First experimental results in actuator-mode have been carried out on a test rig with one isolated linear axis. Figure 10 shows the axis' motion with amplitude of +-2mm from the middle position at a frequency of 1 Hz. The stiffness in this experiment was set to 15N/mm. Tests of the prototype as a damping unit in series with an industrial robot have also successfully been carried out. Thus, the system has proven to be operational, but the main area of application has so far been the forging process. Nevertheless, thanks to the passive compliance allowing adjustable stiffness and to the possibility to measure external forces, the hexapod can be used as six degree of freedom haptic interface with force feedback. Therefore, the control frequency and speed of the device need to adapt to different requirements. One main issue are the delay times between the master (the haptic interface - hexapod) and the slave robot. For the remote control of a dynamic device like a robot a proper feedback time is needed. Usually for telepresence the roundtrip time plays a important role. The definition of the roundtrip time is the data transmission time between the master, the human input device, and the slave robot and backwards. To provide adaptable control of a remote robot a visual or haptic feedback is necessary. Humans generally do not realize short delays or dead times in the signal flow, but big delays may prohibit telepresence. Common delay times of approximately 200ms for a visual feedback and 25ms for haptic feedback are being considered to be ideal. One big advantage of using an antagonistic pneumatic system is the passive stiffness provided by the compression capability of the air fluid. With respect to the position of the actuator, the passive stiffness is adjustable by increasing both the agonist and the antagonist pressure channels. Figure 11 shows the stiffness of the actuator in its middle position with both channels charged with the same pressure. In figure 12 the stiffness depending on the pressure over the whole workspace is visualized in a 3D simulation.

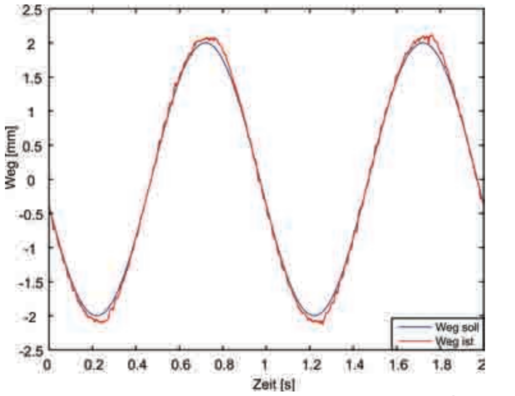

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Fig. 10: *Measurement results based on the test rig of on axis with 1 Hz and +-2mm*

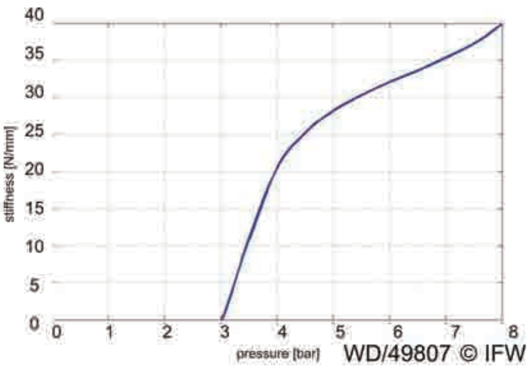

Fig. 11: *Stiffness of one muscle trio in its middle position*

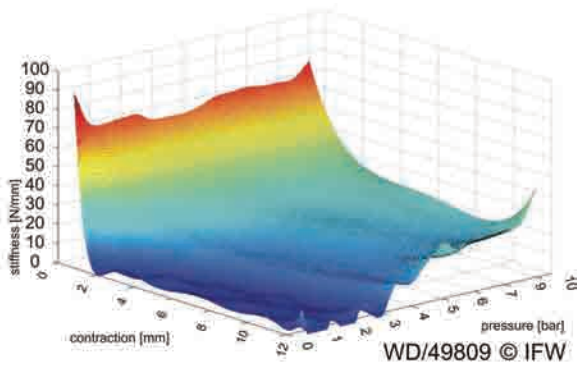

Fig. 12: *Stiffness of the muscle trio over the workspace*

Further investigations will add a model-based stiffness and damper controller, which will provide support of the passive adjustable stiffness with a model-based stiffness. This controller will model a damper and spring in the control loop directly and adapt the commanded position respect to the desired spring and damper. Measurements of the hexapod's stiffness and position accuracy covering the full workspace will also be conducted.

V. Conclusion

To realize and improve the concept of a pneumatic hexapod with both adjustable stiffness and damping and sensory and actory capabilities, different prototype systems have been researched. In particular, these are a single-actuator test rig and the full hexpod structure. The electronic components necessary to control the system have been carried out as a near-industrial application using customized hard- and software. The setup in Figure 13 shows the complete hexapod environment. The current closed-loop control of provides adjustable stiffness and motion control. Prior to the physical production and assembly of the prototype, the hexapod has been tested using co-simulation.. The design of the actuator turned out to be suitable to meet the targeted requirements of “koSePro” in forging processes with robots. The tool may be also used for assembly processes. With the tree developed hardware setups the different application areas of the individual axis units and the assembled hexapod setup have been and will continue to be investigated at the Leibniz Universität in Hanover. The construction has been patented and will be introduced into the market as a serial product by an associated industrial partner company. Further enhancements will include more sophisticated valves (micro piezo valves) that will be implemented together with the pressure sensors and axis controllers in the axis itself.

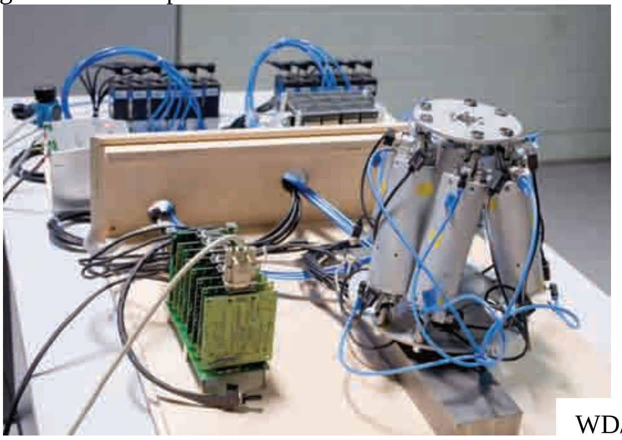

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Fig.13: *the hexapod prototype stage with electronics, valves and power unit*

The sensory capability and a possible haptic usage of such a system to navigate a robot is investigated as a basic principle. In spite of the relatively low communication speed, such an application appears to be suitable. The usage as serial damping unit has been successfully tested

Due to the limitations in communication speed, the hexapod, in the range of full body feedback device, seams to be very suitable for a haptic device although a higher communication speed is desirable.

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