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The QuadHelix-Drive – An Improved Rope Actuator for Robotic Applications

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Abstract – **For the constantly growing service robotic market there is a demand for new energy-efficient and economically priced actuation-concepts. This paper describes the QuadHelix-Drive, a novel rope actuator of high power density with a simple working principle. It highlights the technical challenges, which evolved while examining the DoHelix-Muscle-Concept. A strategy to overcome these challenges and a prototypic mechanical realization of this new actuator concept are illustrated. The integration of the QuadHelix-Drive into the Fraunhofer IPA testing facility is described and at the end possible robotic application scenarios are outlined.**

I. Introduction

Robots and robotic applications use a variety of actuation concepts. Electrical motors, hydraulic actuators, pneumatic muscles [1] and many more are used to enable kinematics to perform their tasks. For the past fifty years industrial robots were in the main focus of actuator development. The focus there was on precise positioning and high stiffness rather than on compliance [2], energy consumption and low costs.

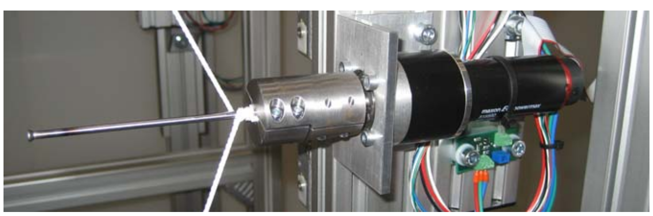

Fig. 1 DoHelix-Muscle

One approach to meet these new demands is the DoHelix-Muscle Concept [3], [4], developed at the Fraunhofer IPA and shown in *Fig. 1*. For the DoHelix-Muscle a DC motor is combined with a turning shaft and a high-strength and highly flexible plaited rope. By coiling the rope onto the shaft from two opposing sides, the radial shaft-forces are compensated and a gearbox-like reduction is realised by choosing a small shaft diameter. Resulting advantages of this actuator-concept are a high degree of efficiency, a high power to weight ratio combined with a low-price. Usage scenarios are newly developed bionic robotic structures [5], [6], active prosthesis [7], and exoskeletons [8], [9].

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II. Technical Challenges

The main challenge for using the DoHelix-Muscle in a robotic application is to have a more compact system with an improved reliability. To learn more about the behaviour of the actuator a testing facility was constructed [10]. With this testing facility challenges for a further improvement of the DoHelix were identified.

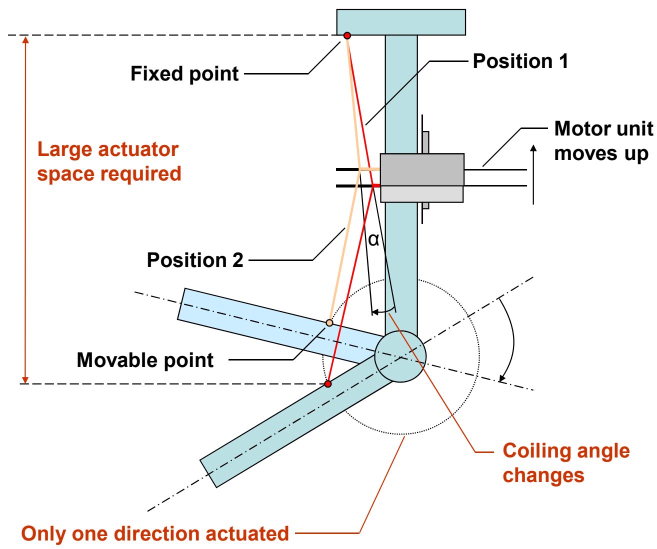

Fig. 2 DoHelix layout challenges

First of all for most biologically inspired actuator systems, including the DoHelix-Muscle, two opposing actuators are necessary to rotate a joint in both directions [11]. This increases overall system weight, because two motor units and two motor controllers with all their additional parts and cables are needed. This also increases the intricacy of the control architecture.

Second, the current layout of the DoHelix as proposed in [3] and [4] consumes too much space, as shown in *Fig. 2*. To avoid an incorrect coiling of the rope and consequently an unwanted leap in the rope force and rotational speed a certain coiling angle has to be guaranteed. The DoHelix-Layout can only reach this by leaving enough space between the two fixing points of the rope. Thereby it guarantees a slight and tolerable change in the coiling angle. This layout is insufficient for compact applications.

The last challenge identified for an improved rope actuator is the long term durability, which plays an important role in lots of potential application scenarios. Certain values of durability and of bearable duty cycles have to be reached,

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e.g. most rope actuated robot systems, which use steel cables instead of HMPE ropes for actuation, have certain defined intervals to change their rope components, e.g. 40.000 cycles [12].

III. Solution Strategy and Conception Stage

To address these challenges some new approaches were necessary. So the first step was to try to build a more compact system. To improve the actuator, mechanical models were needed. The first iterative model combined two DoHelix-shafts that were using only one motor unit, as shown in *Fig. 3.* This approach reduced system weight, but also reduced efficiency by integration of three gear wheels. Furthermore, the incorrect coiling problem still was not solved with that and so the maximum rotation angle around the axis still was limited.

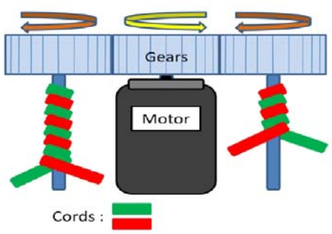

Fig. 3 First idea for an improved actuator

The second approach was to use one shaft to do both DoHelix-coilings (5 and 6) on it, as shown in *Fig. 4*, *A*. For that, the motor unit (1) was fixed and a worm gear (2) on the shaft translated the whole pulley-rope-guiding-mechanism on a linear axis (4). This system was much more compact than earlier ones. It allowed a smooth coiling at all times and a compact actuator system. Disadvantage of variant A was that the pulley-rope-guiding-mechanism is a movable part and it tended to get caught in stick-slip-effects. The repeated change of the pulley positions relatively to the turning wheel caused unwanted nonlinearities in rope angle and rope force.

So the final approach using variant B for the new compact actuation system just switches the moving part: Instead of moving the guidance mechanism, the motor unit is moved, as shown in *Fig. 4*, *B*, on a linear axis. To keep the coiling smooth and at the same position at any time, the module of the worm gear used to translate the motor unit against the fixed gear rod (3) is exactly adapted to the rope and shaft diameter. For that the translational axis (4) velocity $v_{motor\ unit}$ of the motor unit has to be directly proportional to the rotation speed n_{shaft} of the shaft. The worm gear thread p per rotation has to be two times the rope diameter d_{rope}, because two ropes are coiled per turn.

$$v_{motor\ unit} = 2 \cdot d_{rope} \cdot n_{shaft} \tag{3.1}$$

So two rope ends of the first DoHelix-coiling (5) are guided over two pulleys (7) and are pulling the turning wheel (8) into one direction, while the other two rope ends of the second DoHelix-coiling (6) are working in the opposite way. With this new layout, named QuadHelix-Drive because of its usage of two DoHelix-coilings, an improved actuator system is possible.

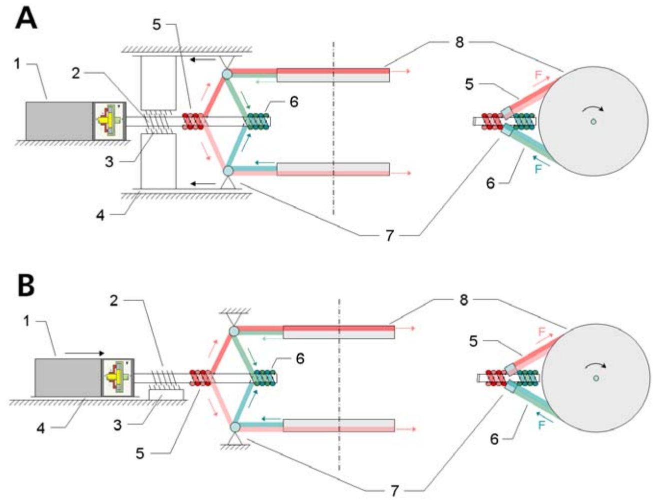

Fig. 4 QuadHelix: Variants A and B

IV. Mechanical Realization

The next step towards a new system is the mechanical realization. To show the potential of the actuation concept a CAD prototype is drafted, as shown in *Fig. 5*.

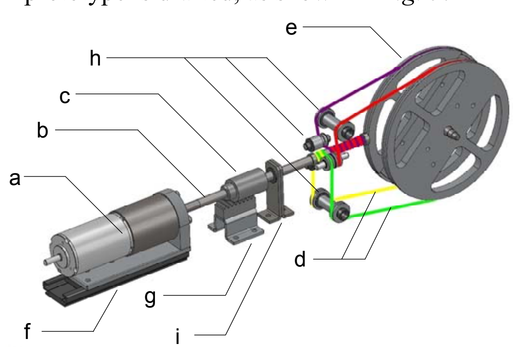

Fig. 5 QuadHelix CAD prototype

This prototype consists of a 200 W motor unit with a small gear box (a), with a reduction rate between 4.3:1 for the testing facility and 61:1 for a 2-DoF-module in a robotic arm. A long shaft with 6 mm diameter (b) with a worm gear (c), two 1.5 mm diameter DoHelix ropes (d) with a breaking load of 2200 N and two aligned 100 mm turning wheels as representations of a 1-DoF-axis (e) are other key components. In addition, the motor unit is placed on a linear guiding rod (f), the worm gear has a fixed linear gear rod as a counterpart (g) and the two DoHelix ropes are guided to the aligned turning wheels by eight pulleys (h). The shaft needs only a small counter bearing (i), because the rope forces onto the shaft compensate themselves. All guidings and bearings are realized with high performance plastic bearings to reduce overall system weight. The elements for pre-tensioning the rope are not shown in this model. They are located between the pulleys and the turning wheel itself. These parts make up the first prototype of the QuadHelix-Drive. The lightweight HMPE ropes for power transmission reduce the overall weight and thereby increase the mass-related torque-density. In *Fig. 6* the movement of the actuator is shown while rotating the turning wheel. The motor unit turns the lower side DoHelix-coiling to rotate the turning wheel, while at the same time the upper side DoHelix-coiling is uncoiled through the rotation of the turning wheel.

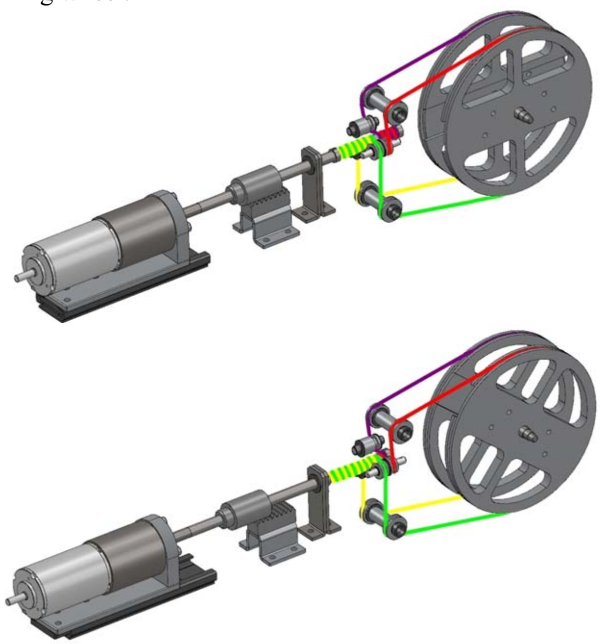

Fig. 6 QuadHelix CAD prototype turning wheel movement

A first rough calculation of the available torque at the turning wheel axis starts with the shaft torque M_{shaft}. For that the nominal motor torque M_n is multiplied with the gearhead reduction R_{gh} and the maximum efficiency η_{gh} of the gearhead.

$$M_{shaft} = M_n \cdot R_{gh} \cdot \eta_{gh} \qquad (4.1)$$

The shaft speed n_{shaft} is the maximum output speed of the gearbox, which is the maximum input speed $n_{gh\,in}$ divided by the gearhead reduction.

$$n_{shaft} = \frac{n_{gh\,in}}{R_{gh}} \qquad (4.2)$$

Some assumptions are made in advance: The worm gear unit reduces the maximum output torque, because it uses some energy to translate the motor unit. The energy used for this depends on the mass of the motor unit and its direction relatively to gravity. In a system like a robotic arm, this energy consumption changes with the current position of the whole system. Because first tests show, that this is a value below 5 % of overall energy consumption, it is for now left aside.

According to [4] and equation *(4.1)*, the contracting force F_c within the rope becomes

$$F_c = \frac{1}{(d_{shaft} + d_{rope})} \cdot M_{shaft} \qquad (4.3)$$

with d_{shaft} being the diameter of the shaft and d_{rope} being the diameter of the rope. In *Fig. 7* the different pulley positions for the rope guiding are shown: One double pulley on the left side and two single pulleys on the right side of the shaft.

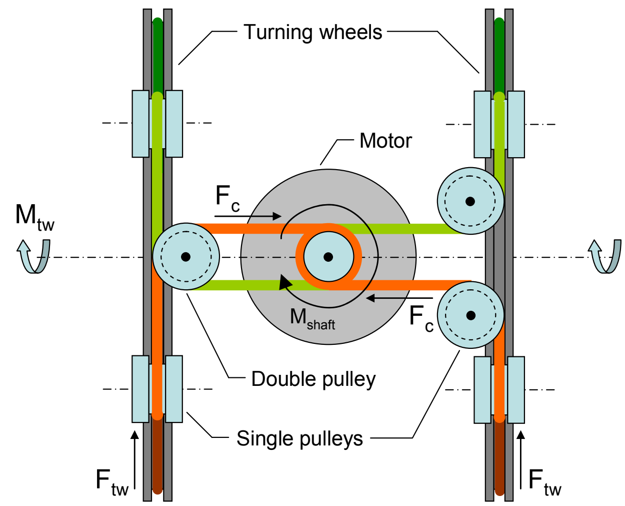

Fig. 7 Front view of shaft: Pulley positions

Using the Euler-Eytelwein-Formula [13] for rope friction the force F_{tw} at the turning wheel is estimated to

$$F_{tw} = F_c \cdot e^{-\mu_0 \cdot \alpha} \qquad (4.4)$$

Mechanical tests to estimate the friction constant μ_0 delivered an average value for the used pulleys of roundabout 0.1. Within the prototype for one direction there are four pulleys used to translate the force with ~ 90° enlacement each, so the enlacement adds up to 360°. With that the available turning wheel torque M_{tw} is estimated to

$$M_{tw} = F_{tw} \cdot (d_{tw} + d_{rope}) \qquad (4.5)$$

with R_{QH} being the QuadHelix reduction between shaft and turning wheels of

$$R_{QH} = \frac{d_{tw} + d_{rope}}{d_{shaft} + d_{rope}} \qquad (4.6)$$

Using equation *(4.2)* and equation *(4.6)* the turning wheel speed becomes

$$n_{tw} = \frac{n_{shaft}}{R_{QH}} \qquad (4.7)$$

With equation *(4.7)* the operation speed of the rotational axis is

$$\omega_{tw} = n_{tw} \cdot \frac{360°}{60s} \qquad (4.8)$$

The length of the coiling area needed on the shaft to coil up both DoHelix-ropes depends on two main parameters: The desired turning wheel angle α_{tw} and the turning wheel to shaft ratio. Parameter α_{tw} is selectable up until approximately ~ 325° while the coiling area x_{coil} is calculated as following

$$x_{coil} = 2 \cdot \frac{d_{tw}}{d_{shaft}} \cdot \frac{\alpha_{tw}}{360°} \cdot d_{rope} \qquad (4.9)$$

To this x_{coil} one has to add a Δx, as shown in *Fig. 8*, giving the rope additional space on the shaft, depending on rope and shaft size to guarantee a smooth coiling. The value for this parameter was estimated. There has to be at least one enlacement left at the end of the desired movement to protect the rope from any cutting forces caused by the sharp edges of the drillings that guide the rope through the shaft.

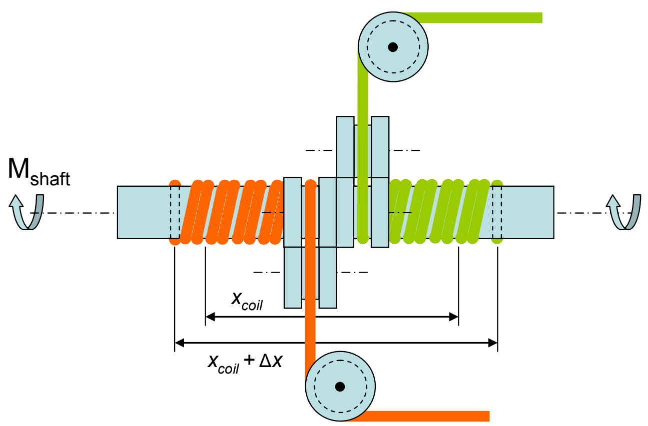

Fig. 8 Side view coiling area

In summary, this layout can actuate both directions, thereby solving one DoHelix-Muscle challenge. At the same time it always guarantees a correct coiling angle on the shaft through the direct connection of shaft rotation and coiling position. This solves the second challenge. Nevertheless, a more detailed analysis has to be done, hereby exactly calculating all energy consumers. The pre-tensioning also has an influence and has to be further examined. The third challenge, long term durability, has to be addressed to the testing facility.

Tab. 1 shows the data sheet for a QuadHelix-Drive with a high efficiency electrical motor. This being an example, the drive is scalable from small sized to large sized applications. The duty cycles are adaptable to any application by changing the shaft to rope ratio. A ratio closer to 10:1 is more likely to sustain a longer time than the current ratio of 4:1.

Tab. 1 QuadHelix-Drive data sheet

QuadHelix-Drive		
Motor unit	Maxon EC powermax 30, 200 W, 24 V with GP 32 C 66:1	
d_{rope}	1.5	[mm]
d_{shaft}	6	[mm]
d_{tw}	100	[mm]
$n_{gh\ in}$	8000	[rpm]
n_{shaft}	121.2	[rpm]
n_{tw}	9	[rpm]
ω_{tw}	54	[°/s]
α_{tw}	220	[°]
x_{coil}	30.6	[mm]
M_n	0.114	[Nm]
M_{shaft}	5.3	[Nm]
M_{tw}	38	[Nm]
η_{gh}	0.7	[-]
R_{gh}	66 : 1	[-]
R_{OH}	13.53 : 1	[-]
F_c	702	[N]
F_{tw}	375	[N]
$v_{motor\ unit}$	6.1	[mm/s]
$m_{motor\ unit\ with\ shaft}$	0.8	[kg]
$m_{QuadHelix}$	1.8	[kg]
Duty cycles of rope	> 30.000	[-]
Power consumption	~ 8 A x 24 V at M_{tw}	[W]
Dimensions [L xWxH]	420 x 60 x 100	[mm]

V. Experiments and Results

The third and the fourth row of the six testing rows of the Fraunhofer IPA testing facility were redesigned and fitted with the new concept to address the third challenge. *Fig. 9* shows a CAD-model of the testing facility with the integrated QuadHelix-Drives in row 3 and 4.

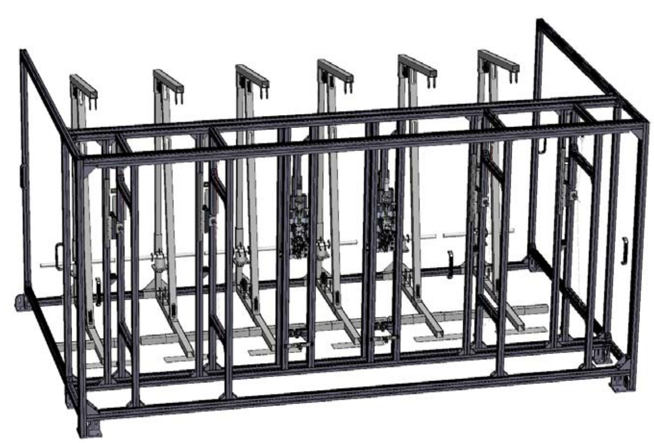

Fig. 9 Testing facility with QuadHelix-Drives in row 3 and 4

In *Fig. 10* the QuadHelix-Drive within the testing facility is shown in a front and a side-view. The motor unit (7), which is placed on a movable platform (8), is here connected to a spindle (6) that runs in a nut (5), realizing the axial movement. This is the first module of each row. The second module is a connector (4), which links the spindle to the QuadHelix shaft with the two DoHelix-coilings on it. This coiling and guiding area (3) is used to build up the pre-tension for the rope and guide it properly to the turning wheel (2). The turning angle is measured via an absolute measurement sensor (1). The third modular area is the outer side of the turning wheel, where in this case two ropes are attached (9) that can move a variable payload in the back area of the testing facility in two directions.

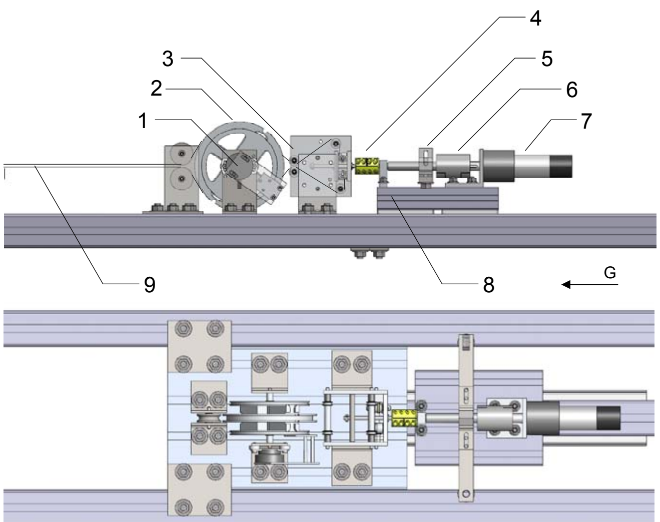

Fig. 10 Side view and front view of QuadHelix in testing facility

The key idea behind this modular construction is a high variability. Different parameters, e.g. shaft diameters, tensioning systems, external sensors and external brakes are testable that way. *Fig. 11* shows the finished QuadHelix system in the Fraunhofer IPA testing field.

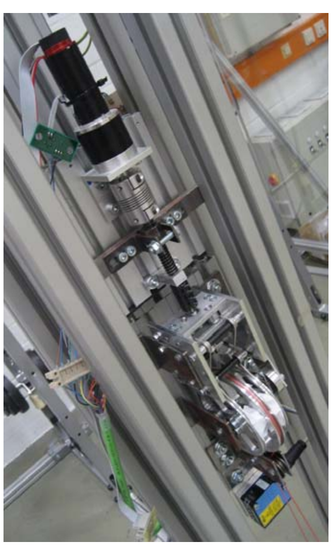

Fig. 11 QuadHelix System in Fraunhofer IPA testing field

Preliminary tests showed an improvement in durability of the actuator system compared to the DoHelix-Muscle. These first results where obtained while the third and fourth rows were still under construction. The results are promising, because they increased the number of load cycles with same speed, acceleration, payload and rope diameter from formerly 3.300 cycles to now 24.000-30.000 cycles. An increased shaft diameter of 5 mm was responsible for this augmentation, as shown in *Fig. 12*. Still under research is the influence of the pre-tensioning, which increases because of more pulleys used in the system. The last of the three challenges is solvable with this approach. *Fig. 12* also shows the dependency of rope force and number of bearable cycles for a 5 mm shaft with 9.6 kg payload in tests no. 1 and 2 and 12.5 kg payload in tests no. 3 and 4.

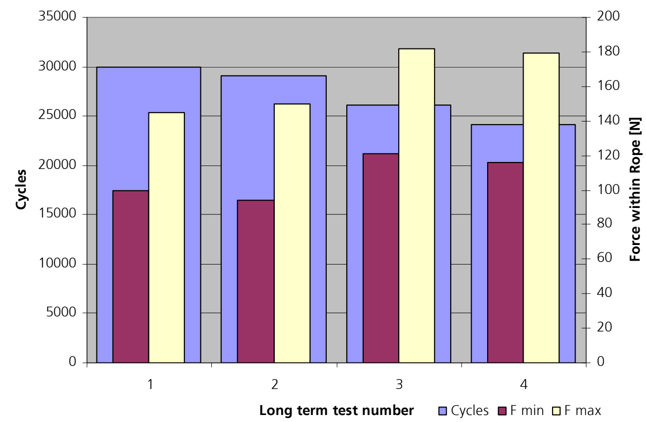

Fig. 12 Preliminary test results

VI. Application Scenarios

With this new drive solution new robotic systems are possible. Currently two projects take advantage of this drive concept. The first project, the development of ISELLA 2**,** a lightweight robotic arm, was finished in July 2009 and it shows the capabilities of the actuation concept for a robotic pick and place scenario in SMEs. *Fig. 13* and *Fig. 14* show the finished ISELLA 2 that uses four QuadHelix-Drives for 4-DoFs and has 3 additional DoFs in its gripper.

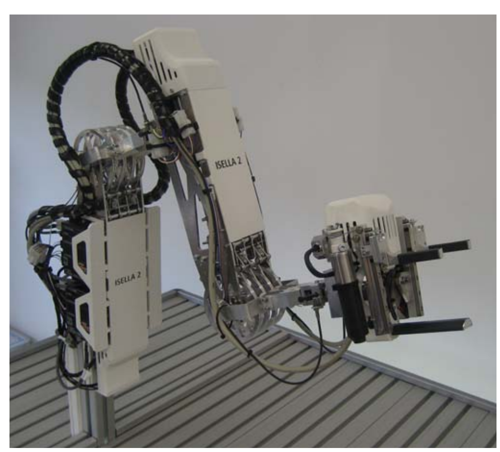

Fig. 13 ISELLA 2 close-up view

Energy consumption measurements of the robotic arm during a pick-&-place-scenario with a 1 kg object yield to an average value of less than 80 W. Furthermore, the mass-related torque-density of 8.45 Nm/kg for the first DoF and 1.35 Nm/kg for the second DoF of a 2-DoF-module is high compared to other approaches [14]. These are only examples for the high efficiency of the whole actuation system and the possibilities for robotic applications.

Fig.14 ISELLA 2 within Fraunhofer IPA testing field

The second project is an active ankle foot orthesis powered by a QuadHelix-Drive, which is still under development. *Fig. 15* shows the latest version of the concept, which uses one QuadHelix-Drive to do the dorsiflexion and plantar-flexion.

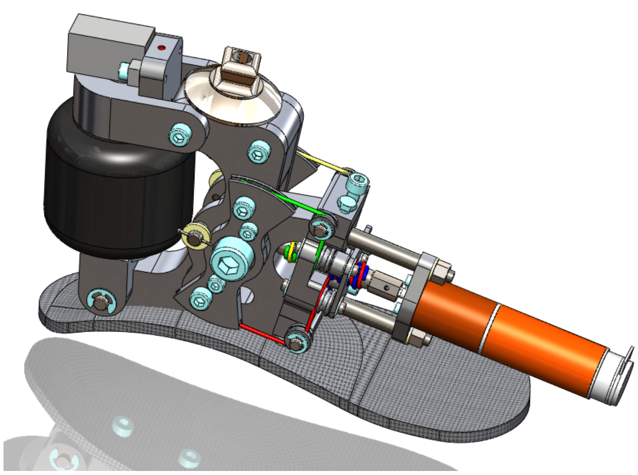

Fig. 15 Active ankle foot orthesis with QuadHelix-Drive

VII. Conclusion and Future Work

The QuadHelix-Drive shows a way, how a compact and powerful rope actuator can be used in robotic applications. The key challenges of the DoHelix-Muscle were addressed and a new drive concept was developed. First applications in a lightweight robotic arm and in an active ankle foot orthesis are developed and next steps are an evaluation and a performance measurement. A detailed system analysis, the optimization of key components and a mobile implementation will follow. For future close-to-market products the main focus will be on cost reduction, simplification and optimization of used materials. Future work also contains a miniaturized version of the actuation concept for energy-efficient and autonomous systems.

VIII. References

[1] Festo AG & Co. KG, Airic`s Arm, 2007 http://www.festo.com/cms/en-gb_gb/5009.htm, 14.08.2009

[2] Vanderniepen, I.; Ham, R. van; Naudet, J.; Damme, M. van; Versluys, B.; Vanderborght, R.; Lefeber, D. (2007) Novel compliant actuator for safe and ergonomic rehabilitation robots – design of a powered elbow orthesis; 2nd IEEE International Conference on Rehabilitation Robots 2007, June 12-15, page 790-797

[3] Staab, H.; Sonnenburg, A.; Hieger C. (2007) The DoHelix-Muscle: A Novel Technical Muscle for Bionic Robots and Actuating Drive Applications; 3rd IEEE International Conference on Automation Science and Engineering CASE 2007, page 306-311

[4] Staab, H.; Sonnenburg, A. (2007) Studies and Guidelines on the Design of the DoHelix technical muscle; 13th IASTED International Conference Robotics and Applications 2007, August 29-31

[5] Klug, S.; Möhl, B.; Von Stryk, O.; Barth, O. (2005) Design and Application of a 3 DOF Bionic Robot Arm; 3rd International Symposium on Adaptive Motion in Animals and Machines AMAM 2005, September 25-30

[6] Klug, S.; Möhl, B.; Von Stryk, O. (2006) Design and Control Mechanisms for a 3 DOF Bionic Manipulator; 1st IEEE / RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics 2006, February 20-22

[7] Au, S. K.; Weber, J.; Herr, H. (2007) Biomechanical Design of a Powered Ankle-Foot Prosthesis; IEEE 10th International Conference on Rehabilitation Robotics 2007, June 12-15

[8] Kawamoto, H.; Sankai, Y. (2002) Power assist system HAL-3 for gait disorder person; 8th ICCHP 2002, July 15-20

[9] Zoss, A. B.; Kazerooni, H.; Chu, A. (2006) Biomechanical Design of the Berkeley Lower Extremity Exoskeleton (BLEEX); 11th IEEE/ASME, page 128-138

[10] Rost, A.; Pfeiffer, K.; Hägele, M.; Verl., A. (2008) Concept and Development of a Testing Facility for a Rope Kinematic Actuator; 39th ISR International Symposium on Robotics 2008, October 15-17

[11] Suzuki, M. (2007) Complex and Flexible Robot Motions by Strand-Muscle Acutators; Climbing and Walking Robots, Towards New Applications; Itech Education and Publishing, October 2007

[12] Rooks, B. (2006) The Harmonious Robot, Industrial Robot: An International Journal, 33/2 (2006), page 125-130

[13] Gross, D.; Hauger, W.; Schnell, W. (1998), Technische Mechanik 1 - Statik, Springer-Verlag 1998, page 190

[14] Olaru, I. M. C.; Krut, S.; Pierrot, F.; (2009) Novel Mechanical Design of Biped Robot SHERPA Using 2 DOF Cable Differential Modular Joints; IEEE/RSJ International Conference on Intelligent Robots and Systems 2009, October 11-15