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DESIGN OF A PHASE – SHIFTING DOUBLE – WHEG – MODULE FOR QUADRUPED ROBOTS

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ABSTRACT

Following mechatronic design methodology this paper introduces a phase-shifting double-wheg-module which forms an alternative approach for wheg-driven robots. During construction focus was placed on a smooth locomotion of the wheg-mechanism over flat terrain (low alternation of the CoM in vertical y-direction) as well as the ability to overcome obstacles. Simulations using the multi-body simulation tool ADAMS View® were executed in order to prove estimations done. Using the results of simulation and calculation a first prototype was designed, manufactured and tested by experiment.

Index Terms – whegs, mechatronic design, simulation

1. INTRODUCTION AND MOTIVATION

Stable and robust walking over unstructured and unknown terrain is still a challenging task for a robot or an autonomously acting machine. Considering the issue the robot or the autonomously acting machine has additionally to deal with different kinds of obstacles, the implementation of (bio-inspired) legs for locomotion purposes displays a possible approach.

TEKKEN II [6], CHEETAH-CUB robot [14] or BIGDOG [11] are formidable examples for successful bio-inspired walking machines. Thereby it is quite interesting that (while neglecting other design criteria) robustness can be achieved either by complicated software algorithms (BIGDOG), embodiment (well-designed, even compliant mechanics like in CHEETAH-CUB), or a balanced mixture of both.

However, legged robots exhibits some disadvantages due to their kind of locomotion. One major issue is the high number of actuators used. BIGDOG requires 16 [11] and even CHEETAH-CUB featuring a bio-inspired pantograph-like mechanism (c.f. Witte & Fischer [4]) has two actuators per leg and therewith eight in sum [14]. In addition, the proper synchronization of the legs still needs effort in control.

Thus the authors want to highlight another possible, yet established approach for robust robot locomotion: the concept of whegs (like shown in section 2), and their improvement. Fig.1 illustrates the principle of a wheg (wheel + leg) and its derivation from a wheel. Thereby a wheg consists of a center (hub) and a different number of fixed spokes. According to application and aim, the spokes might be bendy or stiff.

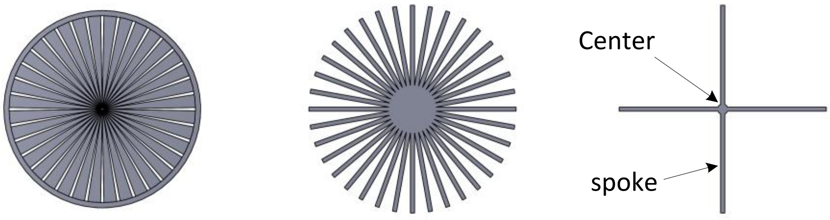

Fig. 1: illustration of a wheel and two whegs consisting of a center and a different number n of spokes

Whegs as a combination of the wheel and leg principles provide advantages of both. They achieve a high horizontal velocity due to the use of a continuously rotating actuator, while keeping control effort low. Aside the spokes give the wheg the ability to overcome obstacles in a leg like manner: 1) A stance phase where the spoke is in contact with the substrate and 2) the swing phase where the spoke is not in contact with the substrate.
By controlling the speed and phasing of a wheg relative to the other whegs, a wheg-equipped robot simply adapts to different environments. Therefore whegs impose efficient dynamic stability and robustness in interacting with unexpected obstacles and terrain.

2. STATE OF THE ART OF WHEG-DRIVEN ROBOTS

The use of whegs, or rimless wheels respectively, is no new idea. A brief study of a rimless spoked wheel in 2D with a single degree of freedom was carried out by McGeer. In 1997 Coleman et al. [2] carried out a 3D mathematical analysis including 3D stability of a rimless wheel with rigid spokes rolling on an inclined ramp, considering the effect of gravity.
One of the first robots that used rimless wheels (or whegs) was PROLERO (PROtotype of LEgged ROver) by Alvarez et al. in 1996 [1]. Featuring six simple spokes, driven by a single actuator each, PROLERO preceded the WHEGS^{TM} series as well as RHEX [15]. RHEX, a robot having six rimless wheels with one passive compliant spoke each, was developed in 2001 in Bühler's group at McGill University by Saranli et al. [12]. Each wheg was driven by a single actuator allowing a change of rotational speed of phase of each wheg individually. Being redesigned several times and equipped with differently shaped whegs (e.g. a c-shaped semi-circle), RHEX is able to overcome rough terrain in a stable manner and even human-sized steps with up to 42 % slope [8].
An alternative approach was introduced in 2002 by Quinn et al. [9]. They developed WHEGS^{TM} I; a cockroach inspired robot featuring six whegs, each wheg having three spokes instead of one. Aside the required driving torque is delivered by a single drive and separated towards the whegs by gear mechanisms. Therewith the drive motor is able to run at constant speed instead of accelerating and decelerating like in RHEX during each walking cycle. In addition WHEGS^{TM} I has compliant axles which enable the robot to overcome a large variety of obstacles, stairs and barriers without changing parts of the design. Based on WHEGS^{TM} I Quinn and coworkers developed several other wheg driven robots like WHEGS^{TM} II, DAGSI WHEGS, MINIWHEGS, CLIMBING MINI WHEGS, or SEADOG [15].
Following the idea of having a robust robot for unknown environments DFKI Bremen introduced ASGUARD robot [3]. Its purpose is the use of whegs for autonomous outdoor missions on various harsh substrates. Therewith focus is placed on a proper communication and sensor strategy.

Another small sized wheg-driven robot is WARMOR [5]. Equipped with only four whegs each featuring four compliant spokes (material: glass-fiber reinforced plastics, length: 75 mm, thickness 0.3 mm) the robot is able to deal with unstructured environments covered e.g. with gravel or debris. Due to a balanced mechanical design the robot uses the energy stored in the spokes during touch down for reducing the amount of energy required during next lift off. For robustness purposes the robot is also able to flip without any lack in performance.

3. ADVANTAGES AND DISADVANTAGES OF WHEG DRIVEN SYSTEMS

In summary whegs are an applicable variant if the environment the robot/technical system has to deal with consists of planes and obstacles unknown in size and orientation. Therefore these obstacles might be of random type like stones or debris as well as structured like steps or platforms.

However due to the discontinuous spoke-to-ground contact of the wheg the center of mass (CoM) of the wheg (and therefore the robot) is forced to an alternating movement perpendicular to the substrate. This alternation is considered as smoothness of the wheg-driven system. It is best when the number of spokes n is infinite; the wheg becomes a wheel. The ability to overcome obstacles is poor. The smoothness is worst having whegs with $n = 1$, which results in a high vertical movement of the center of mass, but is the best way to deal with obstacles (compare fig. 3). However all previous wheg-driven systems show limitations either concerning the smoothness or the range of feasible obstacle height. Therefore modifications of hitherto common and widely spread wheg robot design are necessary.

For overcoming higher obstacles than a common wheg does, Hong et al. in 2006 developed a new concept called IMPASS (Intelligent Mobility Platform with Active spoke system) [7]. Here the focus was placed into individual foot placement to overcome even extreme irregular terrain. Therefore Hong et al designed a wheg where the length of each spoke could be actively changed (independent of each other).

To improve this smoothness of wheg-driven robots without losing the ability to overcome obstacles Shen et al. in 2009 introduced WHEEL-LEG HYBRID ROBOT [13]; a design where an additional actuator changes the shape of the wheg between a circle and a semi-circle (by two c-shaped spokes). So the WHEEL-LEG HYBRID ROBOT is able to use a wheel-like configuration while traveling over flat terrain and a wheg-like configuration when dealing with unstructured environment. This principle, but designed as a triple wheel, also was shown by Quaglia et al. in 2013 with their EPI.Q robot family [10].

4. INFLUENCE OF NUMBER OF SPOKES ON WHEG KINEMATICS

Finding a proper ratio between an acceptable smoothness (means less alternation of CoM in y-direction) and good obstacle dealing seems obvious for an adequate wheg design. Therefore the calculation of both design criteria is introduced successively. Fig. 2 illustrates all relevant elements of a single wheg like spoke length r, the number of spokes n the angle between two spokes α (= 360°/n), the height y_{min} using to calculate the alternation y and (theoretically) feasible obstacle height h.

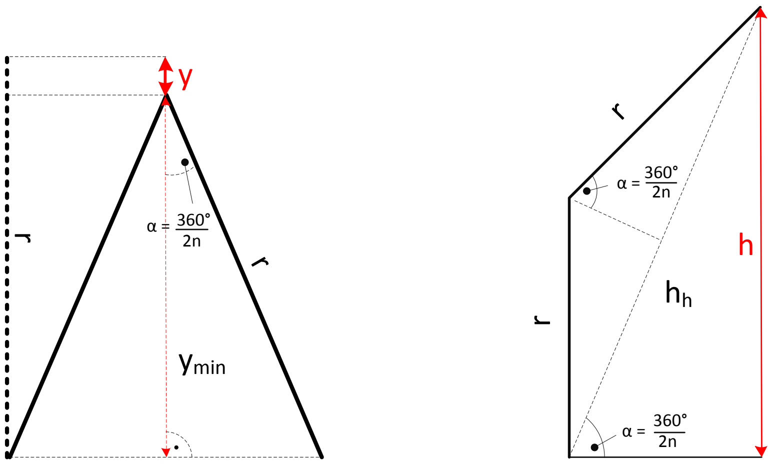

Fig. 2: left: calculation of alteration (= smoothness) in y-direction using y_{min}, **right:** (theoretically) feasible obstacle height h subject to number of spokes n

Due to fig. 2 y_{min} is used to calculate the alternation y. It is described by

$$y_{min} = r \cdot \cos(\alpha) \tag{1}$$

$$y = r - y_{min} \tag{2}$$

$$\alpha = \frac{360°}{(2 \cdot n)} \tag{3}$$

For the theoretically feasible obstacle height h eq. 4 is used:

$$h = \sin(\alpha) \cdot \mathrm{sqrt}\,(2r^2 \cdot (1 - \cos(\alpha)) \tag{4}$$

The results of the alternation of the CoM in y-direction as well as calculation of theoretically feasible obstacle height subject only to number of spokes n is shown in fig 3. Here the percental results eliminating the need for spoke length r are shown.

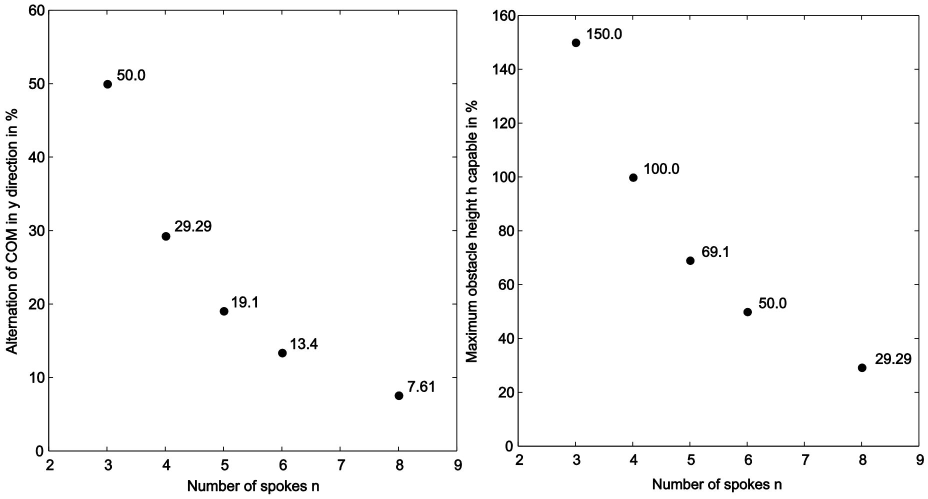

Fig. 3: left: results of percental alteration (= smoothness) of CoM in y-direction, **right:** theoretically feasible obstacle height h both subject to number of spokes n

With increasing number of spokes the alternation of the CoM of the observed single wheg decreases which results in an improved smoothness and a smooth locomotion. But in addition the ability to overcome obstacles decreases, too. For example, having eight whegs, the CoM only alternates 7.61 % of spoke length in y-direction. However the feasible obstacle height amounts 30 % of spoke length only.

To prove these results and for having a model for further investigations (especially for torque required subject to the shape of the robot) a calculation-based simulation was done. Software used is the multi body simulation tool ADAMS View® 2010. Fig. 4 illustrates the investigated model of a single wheg featuring four and eight spokes. Focus of analyze is placed on the vertical movement in y-direction of the CoM of the wheg again. Therefore the wheg is forced to roll on a flat plane. The interaction between ground and each spoke is described by a common Coulomb friction force.

The investigation of the theoretically feasible obstacle height was not done due to the fact that during simulation the foot-down position becomes also important when dealing with feasible heights. Neglecting this influence in aid of an easy first estimation like shown in eq. (4), a comparison to simulation offers no further insights.

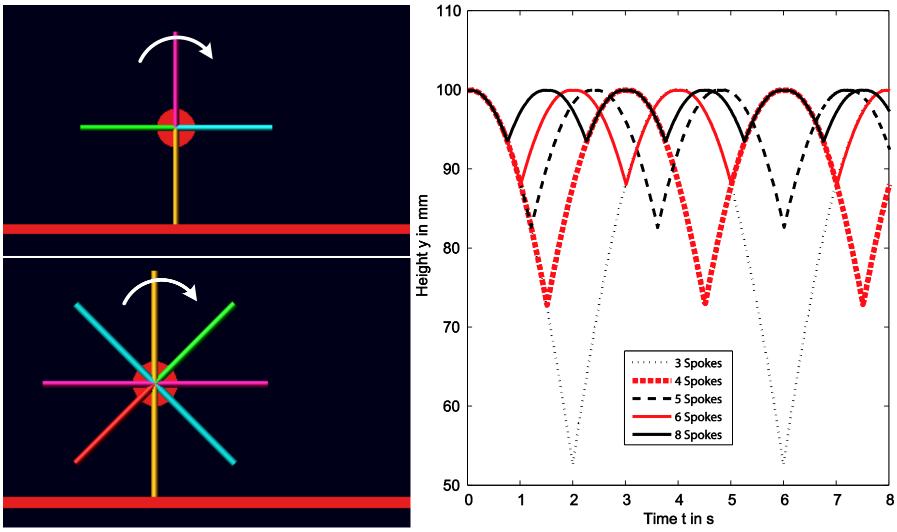

Fig. 4: left: selected models used during simulation, **right:** results of wheg models with a different number of spokes (three, four, five, six and eight spokes) rolling on a flat plane and resulting movement of the center of mass (CoM) in y-direction. Spoke length during simulation: 100 mm, rotational joint speed: 30 degree/sec, simulation tool: ADAMS View® 2010

Fig. 4 confirms the results of eq. 1, 2 and fig. 3. Having a spoke length of 100 mm and a spoke number of four, the CoM varies in y-direction by a maximum of 50 mm which equals 50 %. For eight spokes the CoM varies by a maximum of 8 mm (≈ 8 %).

By following eq. 1 to eq. 4 an acceptable ratio between smoothness and possible obstacle height is favored. In addition to still existing solutions described in section 2 and 3 the authors successively introduce the design approach of the phase-shifting double-wheg-module which offers the ability to change the number of spokes during real-time motion in an active way.

5. THE PHASE SHIFTING DOUBLE – WHEG - MODULE

5.1. Mechanics

In order to change the ratio between smoothness of the robot and possible obstacle height the design of the phase-shifting double-wheg-module is introduced. It consists of a first wheg (outer wheg) which is rigidly attached to a shaft. Around this shaft a hallow axle turns a second wheg (inner wheg). Each shaft is driven by a distinct actuator. Following the results of the simulation each single wheg of the double-wheg-module consists of four spokes. Therefore a change between a wheel-like eight spoke variant for smooth locomotion over flat terrain as well as a four spoke variant for crossing obstacles is feasible. Fig. 5 left illustrates the technical principle.

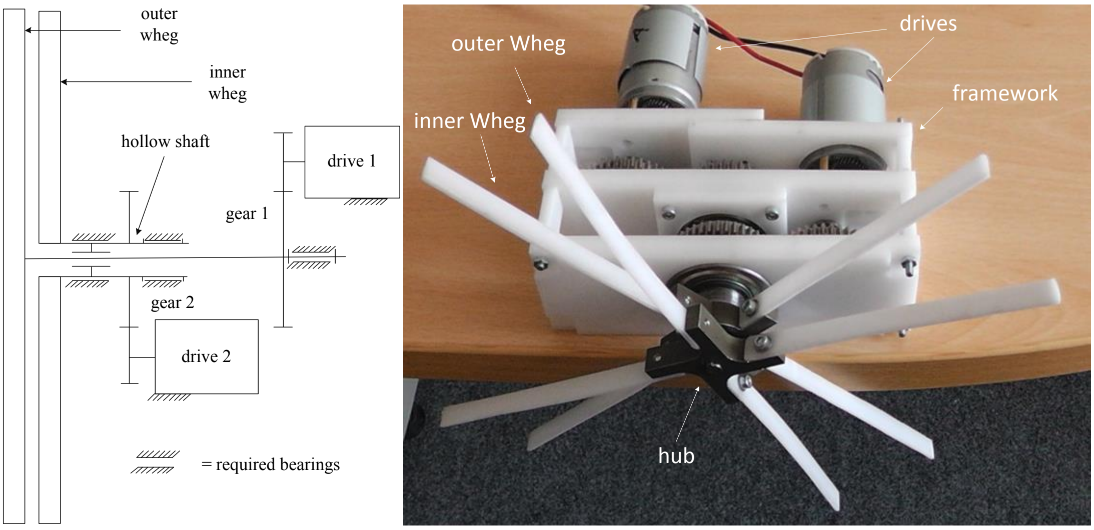

Fig. 5: left: technical principle of the phase shifting double-wheg-module, **right:** assembled version

Having a light-weighted wheg-module for later robotic purposes, the drives are connected to the shafts via a gear (here a 1:1 gear drive). For a quick change of material and geometries of spokes during experiments each wheg hub (material: steel) features a defined interface. During first experiments spokes are considered to be rectangular flat bars. Material used for spokes and framework is POM. Fig. 5 right illustrates the assembled module.

5.2. Electronics and Control

Due to the use of two motors (maxon Inc., no. 222049) with planetary gear boxes the two whegs are able to turn independently of each other. Both motors are driven by a self-made motor-driver and an ARDUINO UNO microcontroller board. Sensors used are rotary encoders from maxon with 32 pulses per revolution. The control loop for a smooth setting of a phase difference between inner and outer wheg is displayed in fig. 6.

It consists of two parts. The first part is a common speed control for the outer wheg (wheg a). It is realized by PI control. The inner wheg (wheg b) is controlled by a cascaded control where the outer loop is the position control. Set value of control is the desired phase shift between the inner and the outer wheg which is compared to the present phase shift: the difference of positions of inner and outer wheg.

Therefore the position control consists of a P-part only while the inner loop of the outer wheg features the same speed control parameters like the inner wheg but feedforward.

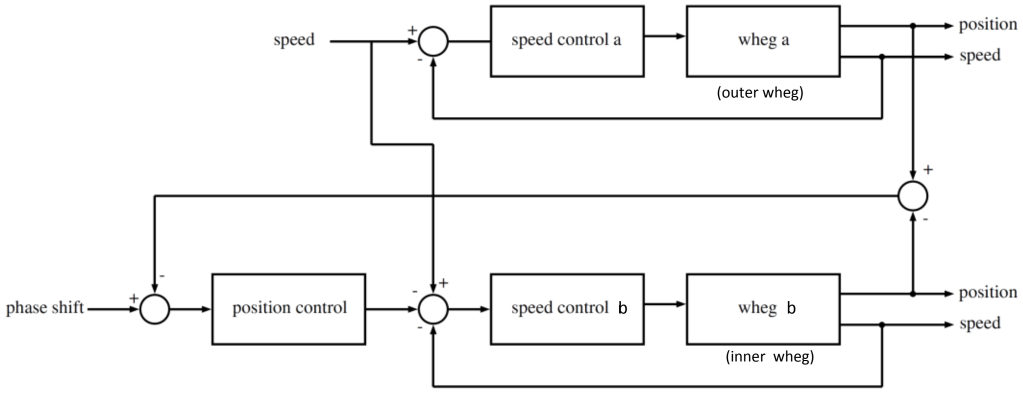

Fig. 6: closed loop control of the phase-shifting double-wheg-module

5.3. Experiments

To test the phase-shifting double-wheg-module, several basic experiments are executed. During all experiments the wheg module was jacked up, so the spokes of the whegs did not contact the ground. The speed was set to 8 rounds per minute.

In fig. 7 the results of maintaining a predetermined phase-shift, here 0°, over the time (≈ 30 s) are shown. All snapshots were taken from KINOVEA motion analysis.

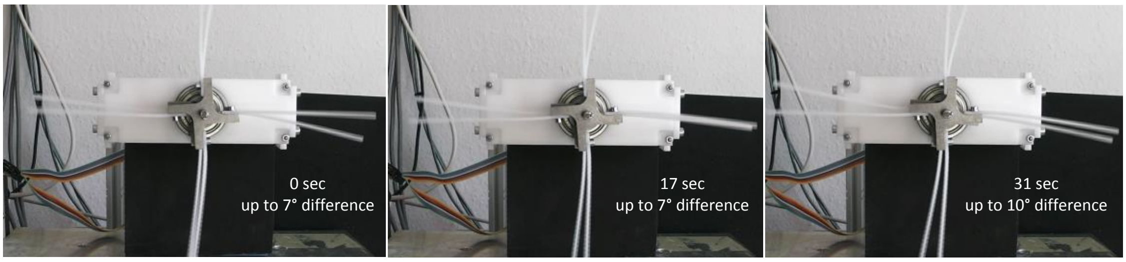

Fig. 7: closed loop control of the phase-shifting double-wheg-module having a set value of 0°

Like shown in fig. 7, the measured present phase-shift (successive named offset) between inner and outer wheg (inside the KINOVEA motion analyzing software) ranges up to 7° due to backlash of the gear and inaccuracy of manufaction (set value of phase-shift: 0°). This range is kept for almost 20 seconds (mid-image of fig. 7). After ≈ 30 seconds, offset amounts up to 10°. However, the offset does not further increase beyond 30 seconds.

For analyzing the ability of the wheg-module to handle disturbances, the wheg module was driven with a set value of 0° again. Although being disturbed (here selected spokes of a wheg were slowed down manually, cp. fig. 8) the offset between inner and outer wheg amounts up to 9°. The time for compensating the disturbance is about 2 s.

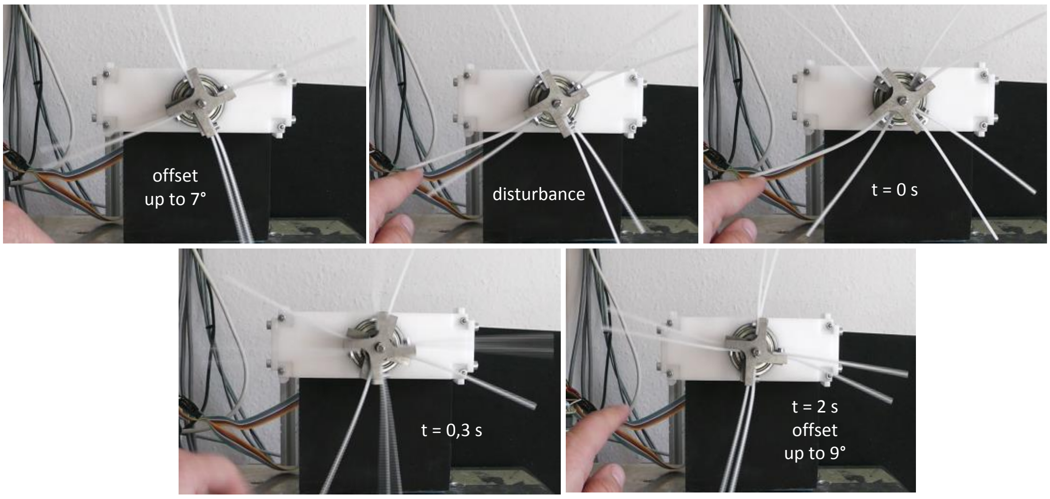

Fig. 8: disturbance of the phase-shifting double-wheg-module

Changing between different set values was investigated in addition. Fig. 9 illustrates the performance of the phase-shifting double-wheg-module when changing the set value from 0° to 45° (time required: ≈ 0.8 s).

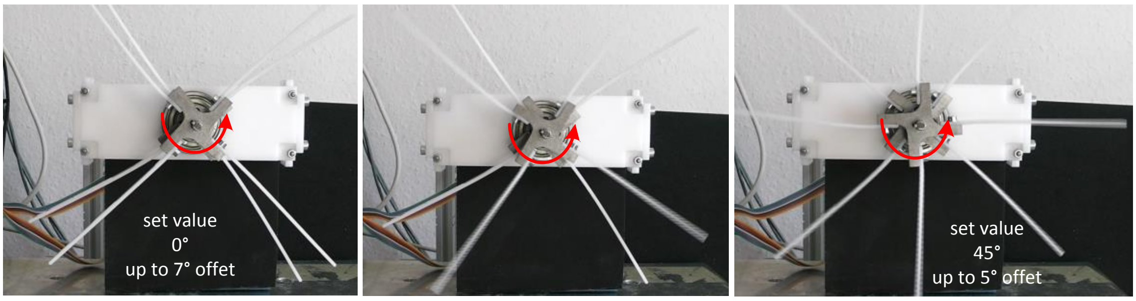

Fig. 9: closed loop control of the phase-shifting double-wheg-module changing set value from 0° to 45°

Therefore the change of set values causes the desired change between a four-spoke and an eight spoke configuration of the phase-shifting double-wheg-module. While having a set value of 0°, offset amounts up to 7° again. A set value of 45° causes an offset up to 5° (measured angle: 50°) between inner and outer wheg.

6. FUTURE WORK

As revealed in section 5 the phase-shifting double-wheg-module needs improvement. Although showing the desired behaviour, the current control loop parameters require fine-tuning for reducing present offset. Therefore a model in MATLAB SIMULINK® will be introduced which represents the latest mechanical setup.

Aside the authors develop an experimental setup for the determination of the alternation of the CoM of the phase-shifting double-wheg-module as well as resulting ground reaction forces. In addition the authors currently investigate a different spoke design by simulation: Instead of having a flat rod a compliant spoke element is desired. Thereby design variants range from a slightly c-shaped spoke with discrete spring elements to a bio-inspired pantographic spoke in order to reduce shocks and to make use of energy recuperation during locomotion.

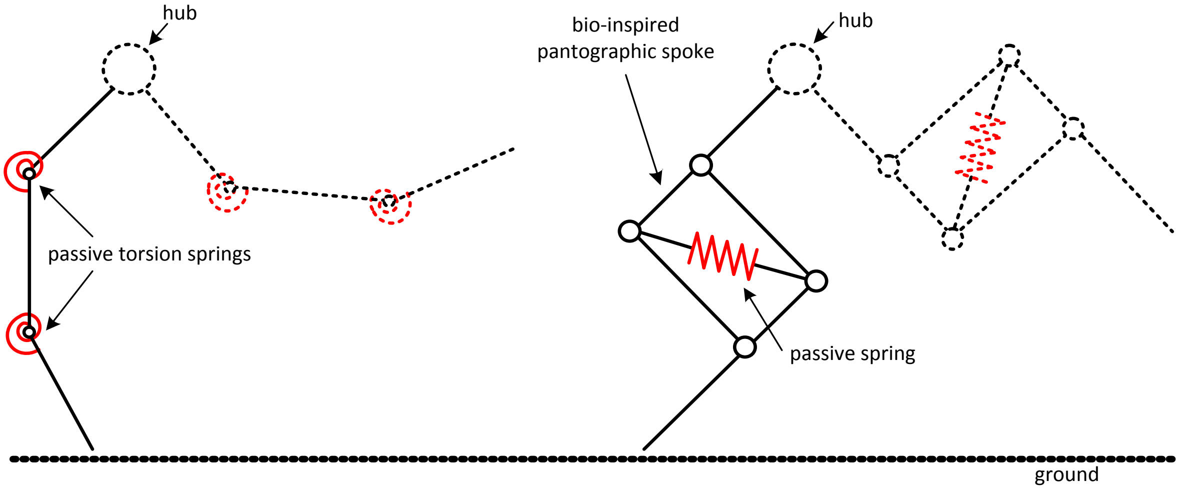

Fig. 10: **left:** design variants of compliant spokes for the phase-shifting double-wheg-module, here a c-shaped spoke with discrete spring elements, **right:** a bio inspired pantographic spoke (only two spokes per wheg are shown)

7. CONCLUSION

The article introduces a new variant of a wheg design, the phase-shifting double-wheg-module. This module enables a smooth locomotion on flat ground as well as adequate obstacle dealing as a result of the use of an online changeable number of spokes. Due to executed calculations and simulation, the number of spokes switches between four and eight. A first prototype and basic experiments confirm the scheduled operation mode of the phase-shifting double-wheg-module.

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