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Wheg-module with electromagnetic spokes

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ABSTRACT

Based on the mechatronics design methodology a new approach for a wheg-driven robot is introduced. The wheg module with electromagnetic spokes is a wheg appendage with actively controlled spokes, to enhance the whegs performance by decreasing the vibration of the robot during motion over smooth terrains (alternation in the direction perpendicular to the direction of motion), increasing its ability to overcome obstacles without the need to change the design. The wheg was studied using a mathematical model. Simulations using the multi-body simulation tool ADAMS View® were done to help improving the concept. Based on the results from the mathematical model and simulations a prototype for the wheg module with electromagnetic spokes was manufactured, and experiments were done to evaluate the concept.

Index Terms - whegs · bio-inspired robotics · locomotion

1. INTRODUCTION

Locomotive robots can be used in uncountable applications such as exploration, rescue security and surveillance, which require the transportation between different places facing hostile and complicated environments, moving over different substrates from grass to sand to asphalt with different features. Some of them have uniform obstacle such as stairs, and others have irregular obstacles such as holes and rocks. Locomotion should always be enhanced in order to combine several features as fast transportation speed with the ability to overcome different obstacles, consuming the minimum power, while accuracy and robustness are high.

The typical effectors for locomotive robots are wheels, as wheeled mobile robots are energy efficient, can move with high constant speed passing by rough terrains and have simple mechanisms making their control easy. Wheels can control the horizontal component of the ground reaction force by friction, so good interaction with human environments is given. Recent research was directed towards legged robots instead of using wheeled ones, since wheels can go through only less than half of the earth's landmass. Conventional wheels need a prepared surface, avoiding obstacle heights less than the whell's radius, which would make the robot useless in some applications. While legged robots have discrete footprints other than the wheeled ones which are always in contact with the surface, this discontinuous contact with the surface makes it easy for legged robots to step over large obstacles and to adapt to uneven surfaces.

Biomimetics introduces new systems that can overcome the limitations of wheeled systems. Biological inspiration is one of the promising methods which help in enhancing and

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introducing new ideas to the traditional technical systems, it is the starting point in the way for finding new ideas to solve the problems facing traditional man made systems.

2. Background

BIG DOG [1] and CHEETAH-CUB [2] are excellent examples for the bio-inspired legged robot moving in a robust way. The CHEETAH-CUB leg design was based on the pantograph leg design for legged robots suggested in 2001 by WITTE et al. [3], where the authors proposed a pantograph structure for extracting main mammalian leg features. CHEETAH-CUB legs were designed using complaint mechanics, providing it's robustness and its ability to move over rough terrains. BIG DOG robot can move over mud, snow, inclines and different varieties of surface including rutted trails and rocky surfaces. It owns complicated software algorithms which make it move in a smooth way.

Multi-segmented legs need complex actuation schemes which lead to heavy weight and thus poor power to weight ratio. They result in slow transportation speed of the robot. BIG DOG has four hydraulic actuators per leg, so a total of 16 actuators, and CHEETAH-CUB has two actuators per leg, a total of eight actuators. This complex mechanism needs effort in the control in order to synchronize the legs.

Inspiration from nature is not just a blind copy from the environment but it is a way to understand the nature and get new ideas from it, so by the help of motion principles observed in nature new possibilities can be introduced, improving the mobility of the locomotive systems, and give the machine the ability to overcome complex uncertain environment.

So the studies for providing more robust robot locomotion with the ability to move over rough terrains led to the presence of whegs. Wheg (wheel + leg) appendage is a rimless wheel where the spokes of the wheels is in direct contact with the surface. At first the term "wheg" is used for the rimless wheel itself, additionally it is used for the robots which use the rimless wheels as effectors in contact with the surface.

Since the whegs act in both legs' and wheels' like manner it provides the advantages of both wheels and legs. The wheg appendages have the advantage of discontinuous footholds on the surface, alternating between the stance phase where the spoke is in contact with the surface, and the swing phase where the spokes are not in contact with the surface. So it can deal with irregular discontinuous terrain and step over obstacles that are higher than the spoke having the advantage of legs. Whegs do not need complicated actuated system, decreasing the total weight so increasing the payload capacity, increasing the horizontal speed so combining the speed and mobility of wheels and the climbing mobility of legs. Thus the wheg robot stability, robustness and its ability to deal with unexpected obstacles can be achieved by controlling the speed and the phase between the whegs of the robot.

The rimless wheels is not a new idea, in 1997 COLEMAN et. al. [4] studied the mechanics of a rimless wheel with rigid spokes, rolling on a ramp surface under the effect of it weight, where one spoke hit the ground after the other. This led to the transfer of the wheel pivot. The authors provided a 3D model for whegs. A two dimensional study of the rimless spoked wheel was carried out by MCGEER, this 2D spoked wheel had single degree of freedom.

RHex was developed by SARANLI et. al. [5]. It is a robot with six passive compliant legs. Each leg is a rimless wheel with one compliant spoke connected to a single separated actuator, which allows a phase and speed difference between the legs. The six legs move in a tripod gait like the cockroaches, where there are three legs on each side. The front and back leg on one side move in phase with the middle leg on the opposite side, the two tripods are rotating antiphase, when the three legs which are in the retraction phase (in contact with the ground) rotate slowly, while they rotate fast in the protraction phase.

In 2002 QUINN et. al. provided an alternative approach for whegs robot, they introduced whegs I [6] inspired from the cockroaches' motion. It makes use of six whegs as appendages, each is a rimless wheel with three spokes evenly separated from each other instead of one as in RHex, all whegs are derived by one motor through a gears mechanism such that the wheel rotates in constant speed and does not need to change its speed between the retraction and protraction phase. So driving the robot at nearly constant speed also all the onboard power is available to each leg, decreasing the weight, so increasing the power to weight ratio. The six appendages move also in a tripod gait, the appendages are connected to the body through compliant axis in order to change phases between whegs when they come to an obstacle, without the need to change design. Based on these whegs other approaches were introduced by adding some modification. In whegs II [7] a new feature was added to the robot appendix, the whegs robot have a flexible joint at the middle of body which allows the robot to climb higher barriers and event bent the body down while climbing in order to keep the whegs in contact with the surface. Another approach is the mini whegs which are a series of robots that are small in size and uses four wheel-legs for locomotion.

The wheg is a rimless wheel with the spokes in contact with the substrate, so as it rotates each spoke goes through a stance and swing phase. This discontinuous contact with the substrate results in a vibration of the wheg and so the robot body in a direction perpendicular to the direction of motion. This alternation results in decreasing the robustness of the center of mass (CoM) of the robot body as it moves even over smooth terrains. This problem can be solved by increasing the number of the spokes, but as the number of the spokes increases the abilities to overcome obstacles and to move over rough terrains decrease. The number of the spokes is directly proportional to the vibration of the robot body but in the same time it is inversely proportional to the ability to overcome obstacles. For example if the number of spokes equals 1 the obstacle capability will be high but the vibration of the robot body will be maximum, and if the number of spokes tends to infinity (complete wheel) the vibration will be minimum with nearly no vibration, but on the other hand the obstacle capability will be minimum.

Recently different works were directed towards smoothing the locomotion of the whegs while keeping their ability to overcome obstacles. Some of the solutions proposed are passive what concerns power flow, such as using whegs with passive compliant spokes to absorb some of the vertical vibration, or using complaint axes between the wheg appendages and the robot body for modifying the phase between the whegs in a passive way. Other solutions are done in an active way and need power supportive drive components, like the concept introduced by HONG et al. in 2006 [8] IMPASS (Intelligent Mobility Platform with Active spoke system), where a robot uses two hybrid leg-wheels and the spokes of this wheels are controlled in an active way. Each wheel has three spokes, each spoke acts as an active leg Thus it can be used in pushing and pulling the robot during climbing and in uneven surface to control the pitch and roll angels of the robot body with respect to the ground. By this active suspension control each wheel can have three contact points in case of stable stance, or two contact points in case of moving with static stability, or even one contact point in case of climbing high obstacles and moving with large steps.

SHEN et al. in 2009[9] introduced the QUATTROPED (Leg-Wheel Hybrid Mobile Platform). It is a robot with four wheels to smoothly move in the even terrains. These wheels can change their morphology by actuators to half circled wheels, so as to move over uneven terrain and overcome high obstacles, changing from a four wheel vehicle to a quadruped. Another different active solution is a family of robots which uses a wheel leg hybrid locomotion introduced by QUAGLIA et al. in 2013[10].

In order to solve the problem of increasing the wheg robots' robustness with increasing its ability to overcome obstacles, the authors here introduce a new active solution in the whegs appendage, where angles between the spokes of one wheg appendage are controlled the way

that decreasing the angles in case of flat trains leads to minimization of vibration, and increasing the angles in case of attacking an obstacle allows to overcome higher obstacles.
This is realized using spokes from conductive material and adding coils in-between the spokes. By introducing electric power into the coil it attracts the spokes to one each other, decreasing the angles between them, and changing the polarity of the supplied electric power repulses the spokes from each other increasing the angles as shown in Fig. 1.

Fig. 1. A functional principle of the wheg module with electromagnetic spokes

Via the current supplied to the coils, the attraction and repulsion forces can be controlled in a way to keep e.g. a robot using whegs moving in a robust way.

3. MODELING STUDIES

3.1 Influence of wheg's parameters on its kinematics

In this section we start to study the whegs robot in a mathematical way, in order to understand the effect of whegs robot's parameters on its stability during motion, and to control these parameters in an effective way to increase wheg robots' stability with keeping or even enhancing its ability to overcome obstacles. These mathematical models are used to cross-check the results of the simulation approach.
By studying the mechanics of the robot, the equation of motion (relation between the vibrations of the whegs robot in the direction perpendicular to the direction of motion and the different robot's parameters) for only one wheg appendage as a function in time is shown in Eq. 1:

$$\mathrm{Y(t)} = \mathrm{L}\left[\cos\left(\frac{\emptyset}{2}\right) + \left(1 - \cos\left(\frac{\emptyset}{2}\right)\right) . \left|\cos\left(\frac{\mathrm{n}}{2}(\omega \mathrm{t} + \theta_0)\right)\right|\right] \tag{1}$$

Where Y (t) is the vertical motion of the wheg's hub as a function in time, L is the spoke length, Ø is the angle between the spokes, n is the number of the spokes, ω is actuator rotational speed and $\theta_0$is the initial angel of the wheg.

The equation of motion for a wheg with general leg parameters is shown in Fig. 2 for rigid spokes, and we take the ground as the reference frame to get the motion of the center of mass of the wheg (CoM) in the vertical (y-)direction.

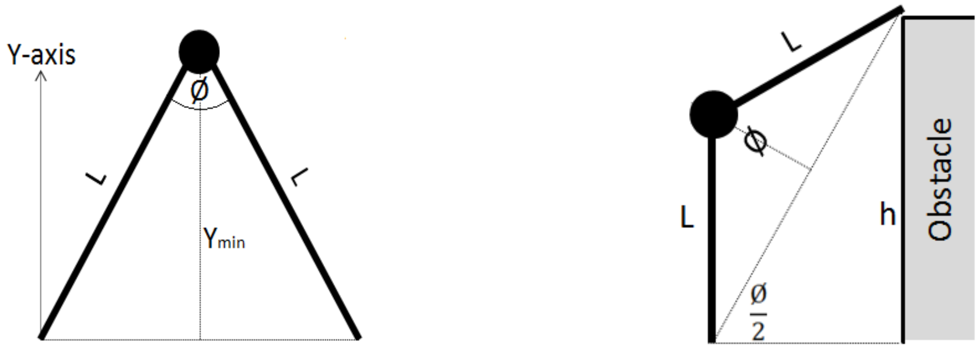

Fig. 2. The wheg appendage parameters in case of motion over smooth terrain (left) and in case of overcoming an obstacle (right).

3.1.1 Influence of the angles between spokes on vibration and obstacle capability

From the previous equation, the hub of the whegs vibrates in a range between the spoke length (maximum height) and the minimum height (Y_{min}) which depends on the spoke length, and the angle between each two successive spokes. The effect of the angle between the spokes on the vertical vibration to spoke's length ratio and the capable obstacle height to the spoke's length ration according to Fig. 2 can be found in Eq. 2 and Eq. 3.

$$\frac{Y}{l} = 1 - \cos\frac{Ø}{2} \tag{2}$$

$$\frac{h}{l} = 2.\sin\frac{Ø}{2} \tag{3}$$

As the angle between each two successive spokes in the wheg appendage affect the alternation of the wheg's hub in the direction perpendicular to the motion direction, it also affects the height of the obstacle the wheg can overcome. As the angle between the spokes increases, the vibration of the wheg decreases - in the same time the capable obstacle high decreases and vice versa. A relation between the angle between the spokes with the vibration and the obstacle high is shown in Fig.3 based on Eq. 2 and Eq. 3.

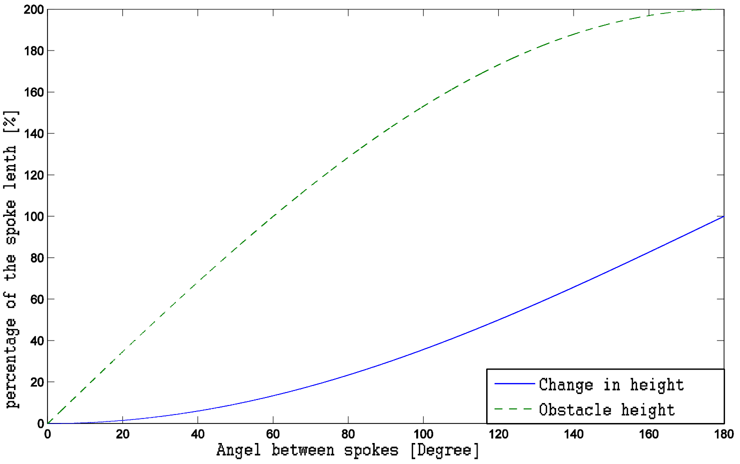

Fig. 3. The curves show percental changes in vertical height subject to the angle between the spokes, and percental obstacle height the wheg can overcome subject to the angle between the spokes.

3.1.2 *Influence of the angles between spokes on horizontal vibration*

The horizontal speed of the wheg depends on the vertical vibration of the wheg as shown in Eq. 4, as the height of the wheg's hub changes also the horizontal velocity of the whegs change, if the height of the whegs alternate in high range also the horizontal speed alternates within the same range. This leads to decrease the mean of the horizontal speed of the wheg. This large alternation in the wheg's hub height happens when the angel between the spokes is large, which happens when the wheg has a low number of spokes. And by the same concept the mean of the horizontal speed increases when the alternation in the height is low.

$$\dot{X}(t) = \omega * Y(t) \qquad (4)$$

If we fix the value of the rotational speed to 1 rad/sec and change the number of the spokes from 3 to 8, which is equivalent to angles between the spokes from 120° to 45°, the relation between the number of spokes in the wheg appendage and the mean of the speed in the horizontal direction in percentage of the spoke length is shown on Fig. 4.

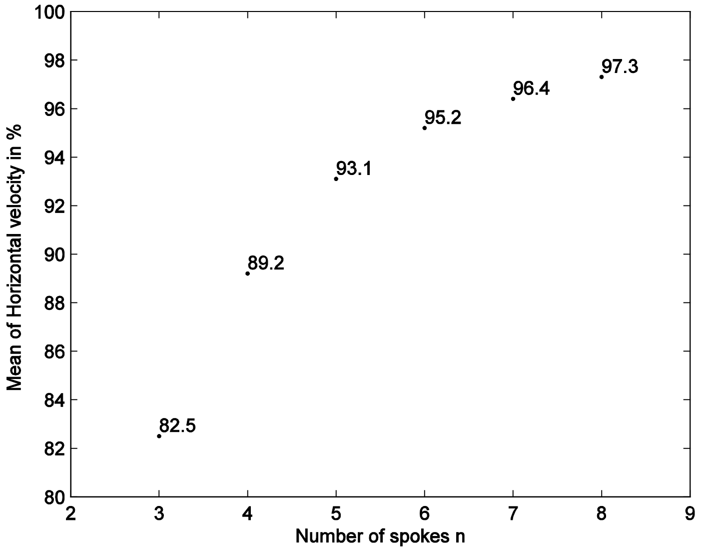

Fig. 4. Results of mean percentage of horizontal speed subject to number of spokes n

3.1.3 *Influence of the phase difference on vertical alternations*

Connecting two whegs commonly with the robot body, the rotation of the two wheg appendages with the same rotational speed lead to an advance of the robot body, where the kinematics of the center of mass of the robot (COM) is greatly affected by the whegs appendages. The center of mass has two degrees of freedom (DoF), different from the normal horizontal motion; it also alternates in the direction perpendicular to the direction of motion. The other DoF is the rotational motion around an axis perpendicular to the robot body (z-axis) with respect to the horizontal axis as shown in Fig. 5.

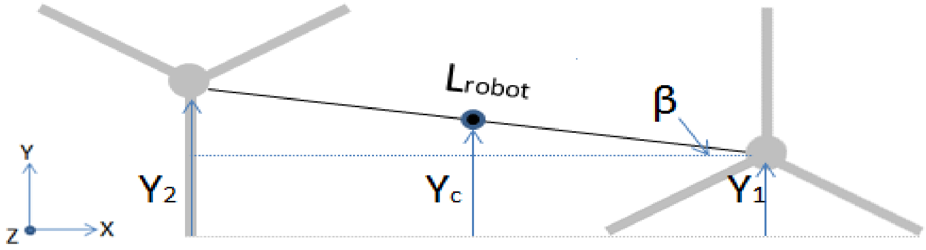

Fig. 5. Calculation of alternation in y-direction and rotation of robot's center of mass

$$Y_c(t) = \frac{Y_1(t)+Y_2(t)}{2} \qquad (5)$$

$$\beta = \sin^{-1}\left(\frac{Y_2(t)-Y_1(t)}{L_{robot}}\right) \qquad (6)$$

Where Y_c is the vertical oscillation of the robot's COM, Y_1 and Y_2 are the vertical oscillations of the first and second whegs respectively, $L_{robot}$is the length between the first and second wheg's hubs, and β is the rotation of the robot body about z-axis.

The vertical alternation for the robot's center of mass depends on the two wheg appendages according to Eq. 5, where the number of the spokes per each wheg or in other words the angle between the spokes of each wheg affects the vertical alternation of the robot's center of mass. The alternation also is affected by the phase difference between the two whegs. In the following Fig. 6, the vertical oscillation is calculated as a percentage of the spoke length for a number of spokes ranging from three to eight. With keeping the two whegs completely out of phase (left figure), also the vertical oscillation is calculated as a percentage of the spoke length.

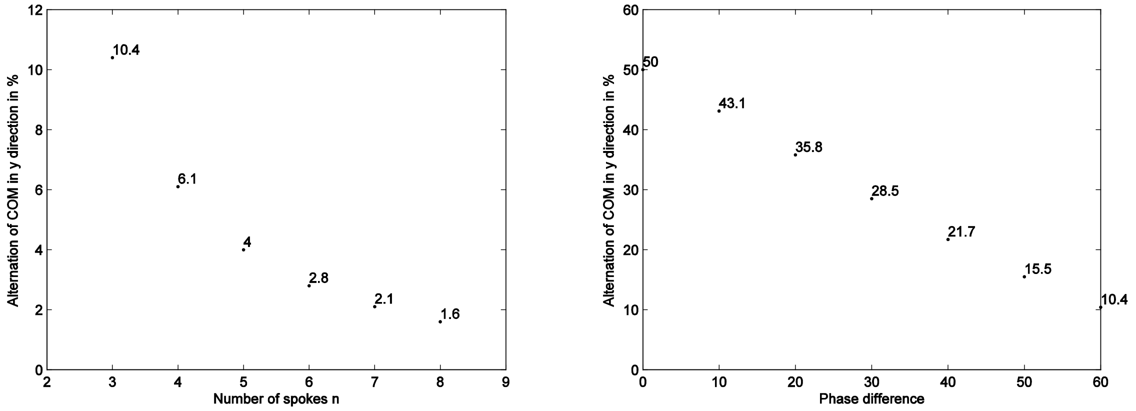

Fig. 6. Percental change in robot's CoM height subject to number of spokes (left) and subject to phase difference between two whegs (right).

4. SIMULATION STUDIES

4.1 Simulating the influence of phase difference on vertical oscillation

In this section we report on simulation studies done using the multi-body simulation tool ADAMS View®. The simulation results provide a proof of concept for the provided idea of the wheg-module with electromagnetic spokes.

First a model for a wheg driven robot was built in the ADAMS® software, shown in Fig.7. The model consists of two wheg appendages connected to a body. The simulation was run for several times with different phase difference between the two whegs, in order to show the effect of the phase difference between the two whegs on the vertical movement (in y-direction) of the center of mass of the body (CoM).

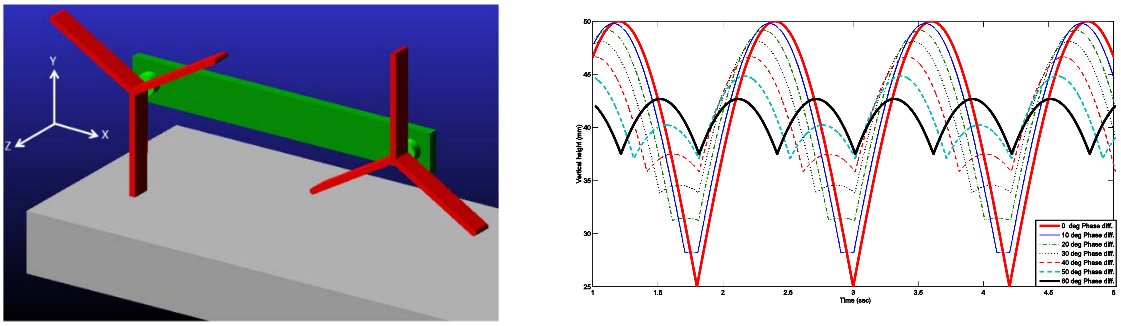

Fig. 7. Model of a wheg-driven robot, the resulting vertical movement of the body's center of mass in a direction perpendicular to direction of movement (y-direction)with different phase difference between the two whegs (during simulation spoke length is 50mm, wheg rotational speed 100 degree/sec and simulation tool is ADAMS View®).

The simulation was run with different phase difference start from completely in phase with phase difference 0° to completely out of phase with phase difference which is equivalent to (360°/2n), as the model was built with three spokes per wheg out of phase equal to 60°,the phase difference increases by 10° from one run to another.

4.2 Simulating the wheg-module with electromagnetic spokes concept

A model in ADAMS View® was build to test the concept of the wheg-module with electromagnetic spokes. Fig. 8 illustrates a complete wheg-driven robot with four whegs appendages, each of them with three spokes, so the angle between each two successive spokes of the same wheg is 120°. All four whegs are in phase (the phase difference equals zero) as we want to show the advantage of controlling the angle between the spokes of the same wheg while neglecting the effect of the phase difference.

The simulation for the wheg-driven robot ran twice, the first time with keeping the spokes of the wheg fixed with 120° between the spokes of each wheg and all the whegs are in phase, the second run was done with controlling the angles between the spokes of each whegs the way that during the motion over the smooth terrain the angles facing the ground are kept as minimal as possible, in order to decrease the vertical oscillation of the robot body according to Eq. 1, thus increasing the robot's stability.

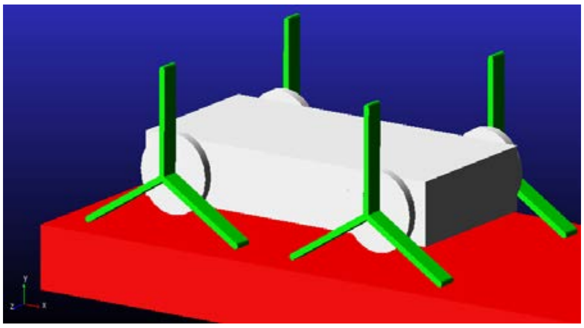

Fig. 8 Model of a wheg driven robot (during simulation, the spoke length equals 50 mm, the joints rotate with a speed of 100°/sec, and the operation was run for five seconds). Simulation tool: ADAMS View®.

In the run with the controlled spokes the angles between the spokes of each wheg was allowed to be controlled in a range from 60° to 180°, so in the first run with the fixed spokes the center of mass of the robot's body oscillates in a range of 50 % of the spoke length, while in case of controlled spokes the newly introduced control algorithm kept the angle facing the ground between the spokes as minimal as possible. Thus the center of mass of the robot's body oscillates in a range of 15 % of the spoke length, so by controlling the angles between the spokes the vertical oscillation is enhanced by 70 % of that in the fixed case. By that way we get the advantage of the six spokes in the vertical oscillation and the advantage of the two spokes in obstacle capability without changing the number of the spokes just by controlling the angle between them.

Controlling the angle between the spokes affects the horizontal velocity of the robot, where in case with fixed spokes the robot body has a mean velocity of 73.6 mm/sec while in case with the controlled spokes the mean of horizontal velocity is 85.6 mm/sec. Thus by controlling the angles between the spokes the mean of the horizontal velocity is increased by 16% in relation to the fixed case.

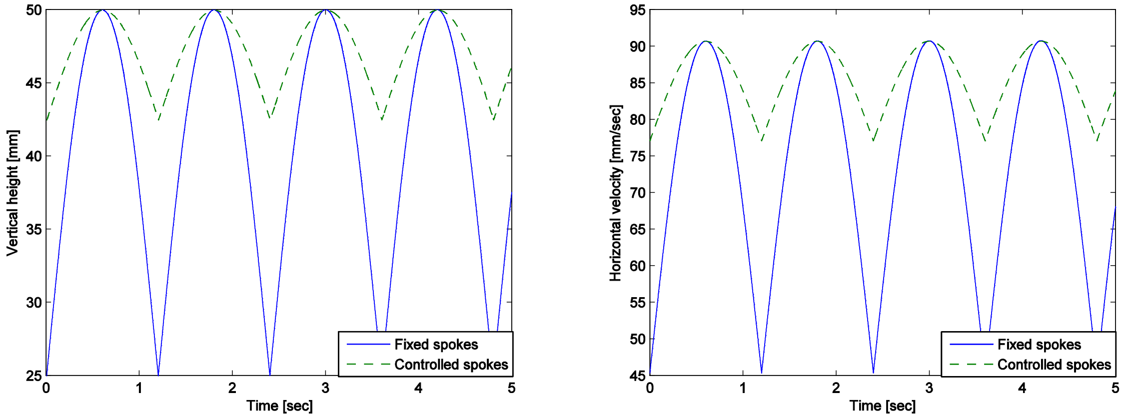

Fig. 9. The two curves compare the resulting vertical alternation (left figure) and the resulting horizontal velocity (right figure) between the fixed and the controlled case

5. EXPERIMENTAL PLATFORM

5.1 Mechanics

To enhance the performance of wheg-driven robots by adding a smart system to increase stability and robustness with increasing ability to overcome obstacles, a wheg module with electromagnetically actuated spokes is introduced. The concept dies not affect design of the whegs to control it stability and obstacle capability, it is done by actively controlling the angle between each two successive spokes of each wheg during motion of the robot.

This can be done by designing the wheg the way that it allows the rotating motion of each spoke in the whegs individually with respect to the wheg itself, around the center of the wheg. So each spoke has two rotational motions, one with respect to the wheg's body, and the other is the rotational motion of the wheg itself with respect to the robot body. The wheg's rotational motion is controlled by a DC motor while the rotational motion of each spokes with respect to the wheg's body is controlled by making the spokes from conductive material and fixing a coil to the wheg's body facing the spokes Thus by controlling the current passing through the coil we can control according to Eq. 7 the force between the coil and the spokes, we even can control the direction of the force whether attraction or repulsion by controlling the direction of the current in the coil.

$$F = \frac{(m.i)^2.\mu_0.A}{2.g^2} \qquad (7)$$

Where F is the force, m is the number of turns, I is the current in area A, $\mu_0 = 4\pi \cdot 10^{-7}$, g is the length of the gap between the solenoid and the conductive material.

In this experiment the whegs have three spokes; they are made from POM material since it has a light weight and is easy to format. Permanent magnets are attached to the spokes facing coils attached to the body of the whegs. Fig. 10 shows the symbolic representation of the idea and the assembled wheg.

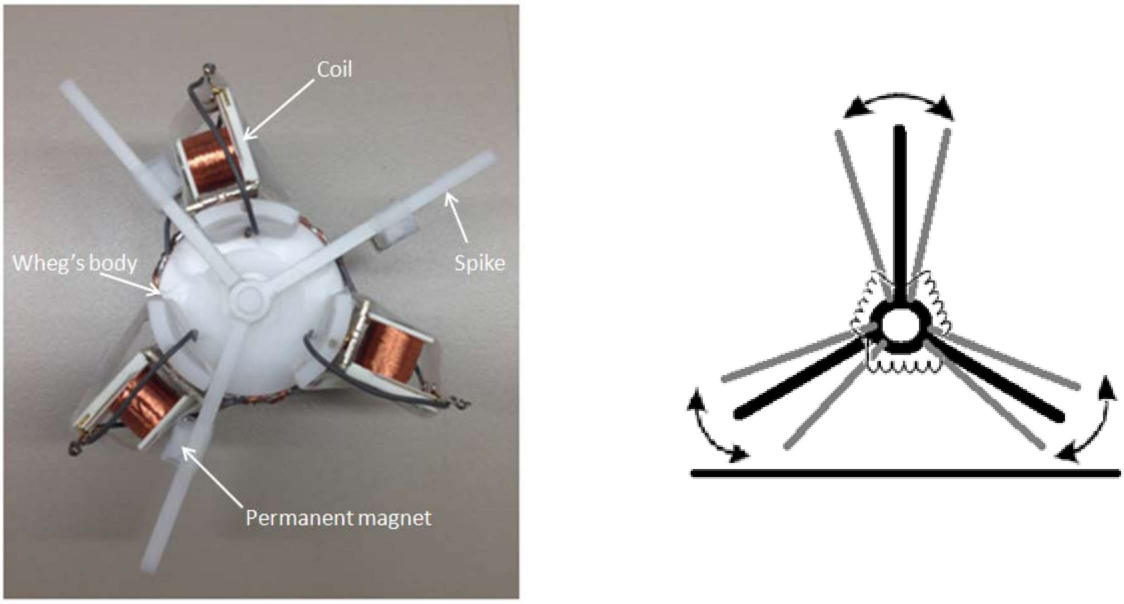

Fig. 10. Assembled wheg (left) and symbolic representation (right)

5.2 Electronics and control

The rotational motion of the wheg is driven by a DC servomotor (Bluebird BMS-303) connected directly to the wheg's axis. The wheg has three coils attached to it so that each coil controls the rotational motion of one spoke with respect to the wheg's body. Motor and coils are actuated by a self made board and an ARDURINO UNO microcontroller board. The current supplied to the motor is measured by a low current sensor (ACS712) with the output also connected to the ARDURINO UNO board.

During the motion of the wheg over a smooth terrain the control algorithm actuates two coils so that it repels the spoke in contact with the ground and attracts the spoke which is going to hit the ground, so that the angle between the two coils facing the ground is kept as minimal as possible, leading to a decrease of the vertical alternation of the wheg's body. In case the controller senses an increase in the current supplied to the motor (which means that the wheg is facing an obstacle), the control algorithm reverses the actuation of the coils so that the spoke facing the ground is attracted and the spoke which is going to hit the obstacle is repelled, to increase the angle of attack to be able to overcome higher obstacle.

5.3 Experiments

In order to test the wheg-module with electromagnetic spokes, two wheg modules were connected via a link bar, as shown in Fig.11. Each wheg has three spokes of 54 mm length each, and each wheg is driven by a separate DC motor. Both whegs rotate in phase with the same speed. The link bar connecting the two whegs is fixed to the global frame, so that it prevents horizontal motion. The setup allows vertical alternation, as we are concerned with the vertical vibration.

The experiment was run twice, the first time with fixing the spokes with 120° between each two successive spokes; and the second time using coils between the spokes and magnets on the spokes, controlling the power supplied to the coils. This was done in order to keep the angle between the spokes facing the ground with the minimum possible value of 74°. It could be observed that in both situations the maximum vertical height is the same (54 mm), which is the spoke length, but the minimum vertical height is different in both cases.

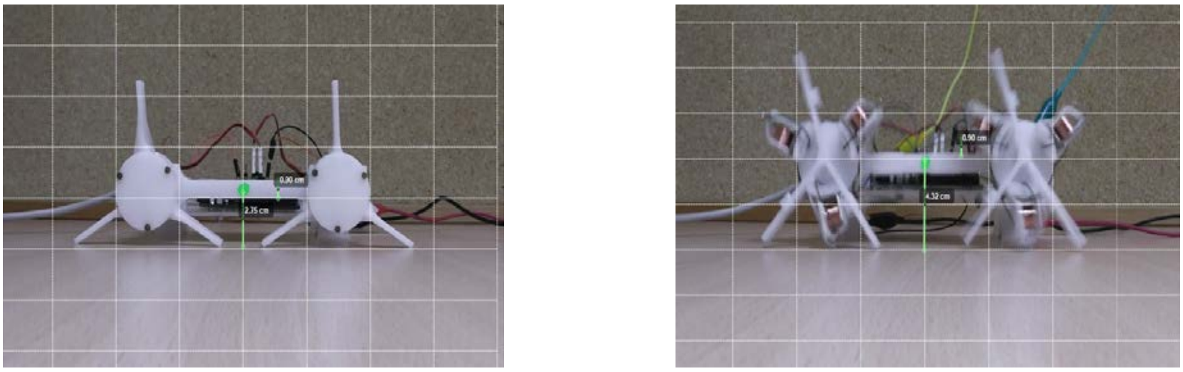

Fig. 11. Showing the minimum height in case of fixed spokes (left) and controlled spokes (right). Snapshots were taken from KINOVEA motion analysis

In case of fixed spokes the minimum height was 27 mm so the body oscillates in 50 % of the spoke length, while in case of the controlled spokes the minimum height was 43 mm, so the body oscillates in 20 % of the spoke length, thus decreasing the vertical alternation by 60 % of that in fixed case.

6. Conclusion

The wheg module with electromagnetic spokes is a new approach for wheg-driven robots, which increases the stability of the wheg robot while increasing its ability to overcome obstacles. This is done online by active control of the angles between the spokes of the whegs. Mathematical, numerical and experimental studies prove the estimated enhancement of the wheg module with electromagnetic spokes.

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