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InchwormClimber: A light-weight biped climbing robot with a switchable magnet adhesion unit

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***Abstract*— This article presents an inchworm climbing robot that is designed with switchable magnets and a single DOF arm. The InchwormClimber works on ferromagnetic structures and consumes little energy when climbing and can descend safely with almost zero energy consumption. Furthermore, considering the critical role of the adhesion unit in the overall functionality of the robot (weight, climbing speed and the payload), we optimized the switchable magnet unit for a higher adhesion force per mass unit.**

I. INTRODUCTION

Climbing robots are now starting to replace human workers in tasks such as maintenance and inspection of tall structures, reservoirs, bridges, pipes, etc... This kind of operations usually involve strenuous physical labor and high risks for the safety, even for skilled workers. This explains the growing interest in the development of climbing robots in the last two decades. The development of autonomous climbing service robots is very important from different points of view: integrity of the infrastructure, safety of the human operators, quality of the inspections and increment of the periodicity of inspection.[1]

Many types of climbing robots have been proposed in the last decades, with different adhesion and locomotion systems. Legged robots, for instance, have higher mobility than the wheeled climbing robots, being capable of easily overcoming obstacles or cracks found in the environment.[2].

Structures having from two up to eight legs have been developed. The adoption of a larger number of legs supplies redundant support and, frequently, raises the payload capacity and safety. These advantages are achieved at the cost of increased control complexity and low moving speed, mostly regarding leg coordination, size and weight.[3]

Therefore, when size and efficiency are critical, a structure with minimum weight and complexity is more adequate. This makes the biped structure a good choice for climbing robots, as this kind of machines need to be as light as possible due to their movement in vertical planes. Biped climbing robots still have many features which are subject of study and optimization. This includes the adhesion mechanism, that should be designed to be suitable for different environments and geometries, and its power consumption that should be as low as possible for a higher autonomy.

For a biped climbing robot, an optimized adhesion unit is characterized by making a minimal friction against the climbing surface when the robot is moving, and offering enough stability for the whole robot when it requires to stay fixed to the structure. Furthermore, the transition between the fixed and the sliding motion should be achieved rapidly and with minimum power consumption. In addition, the adhesion unit should not consume power in an idle condition and should remain attached to the structure in case of a power failure.

A good example of a biped robot is the *SkySweeper*[4], a light and agile biped robot which was developed for moving along transmission lines. Even though it is not a climbing robot, its minimalist design makes it very interesting. It has two clamps, each one driven by a motor that tightens one end to the cable while the other motor drives the central joint of the arm. The fast engagement of the clamps as well as the well designed motor gaits, makes the robot a light-weight, fast and simple example of a biped robot.

An example of a biped climbing robot is 3DCLIMBER, which can climb 3 dimensional structures with bents and branches [5]. Despite its good dexterity, it suffers from a low climbing speed and a complex self calibration controller for positioning of the grippers[6]. It is composed of two large mechanical grasping units and a 4 DOF navigation mechanism.

A similar example of a biped robot is Sharif PCR [7], which is similar to 3DCLIMBER in terms of grasping structure, but rather than a serial climbing mechanism, it benefits from a spatial 3DOF parallel mechanism.

When the surface is ferromagnetic, magnets can be used to provide adhesion force. Magnetic attachment is highly desirable due to its inherent reliability. It can be applied on the chassis of a wheeled based climbing robot [8], [9], [10], [11], [12], [13], [14], [15], or as an adhesion unit for a step-by-step based climbing robot [16], [17], [18].

The evolution of the magnetic holders in general has been made possible by the discovery of new magnetic materials and their continual improvement. Coils, electromagnets or permanent magnets have been extensively used as attachment mechanism. However, for the application of climbing robots, many times it is necessary to control the magnetic force, or at least to switch the magnetic adhesion on and off. For this purpose electromagnets are mostly used. An electromagnet is a type of magnet whose magnetic field is produced by electric current. An example of such climbing robot is *REST* [19], a climbing robot with six legs which is intended for welding in ferromagnetic walls. Its feet use electromagnets as their adhesion mechanism. The machine weights 220 kilograms with a payload of 100kg on vertical structures.

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The Inchworm [20] is a 3 DOF robot with 2 adhesion units with electromagnetic adhesion. Its movement is accomplished by fixing an adhesion unit, and by actuating the motors, move the other adhesion unit, and then make the reverse process in order to achieve a linear movement of the system.

However, the main problem for the application of electromagnets is that they require constant power feed to either stay on or off. Permanent magnets, on the other hand, have no power consumption but they do require a mechanism to be able to vary the magnetic force, either by controlling the gap between the magnet to the surface or by redirecting the magnetic flux, as in switchable magnet devices. Switchable magnets are made with permanent magnets and only require to be powered in order to switch their state. Once switched, they should hold their status without power input. If these devices are coupled with an actuator, their state can be remotely controlled and programmed. Furthermore, as we will show here, the adhesion force such units provide can be controlled. In spite of several uses of switchable magnets in industrial environments, their application in robotics is rather new. There are few examples of robots that take advantage of switchable magnets.

Miche robots[21], use switchable magnets driven by a servo motor on their sides for self-assembly of individual actuated modules. Rochat et. al. discussed development of different types of switchable magnets for applications in mobile robots[22].

Switchable magnets have also been used in mobile robots such as *TERMO* an inspection step by step based robot for ferromagnetic structures [23] and in *Tubulo* a train-like inspection robot for ferromagnetic tubes.

In this paper we introduce a new concept of a light weight and energy efficient climbing robot with switchable magnets and a single DOF arm, the *InchwormClimber*. Its working principle will be similar to the *SkySweeper*, however instead of clamps to move along cables, we will use adhesion units with switchable magnets. Moreover, we show that it is possible to control the force of the adhesion unit with a simple and low power consumption system, allowing to fine-tune the adhesion and friction parameters in order to guarantee both stability and efficiency.

II. INCHWORMCLIMBER

A. The Overall Approach

The climbing mechanism of the proposed robot is intended to have only one degree of freedom and a single actuator. Two other actuators are used for turning the switchable magnets on the adhesion units on and off, as shown in Fig. 1. The locomotion principal of the robot is depicted in Fig. 2.

B. Switchable Magnet Adhesion Unit

The robot has two types of magnetic adhesion on each adhesion unit. The dynamic adhesion is accomplished by using switchable magnets. As a safety precaution, to make sure that the adhesion unit is always in contact with the surface, a static adhesion is made using two fixed permanent magnets, as shown in Fig. 3.

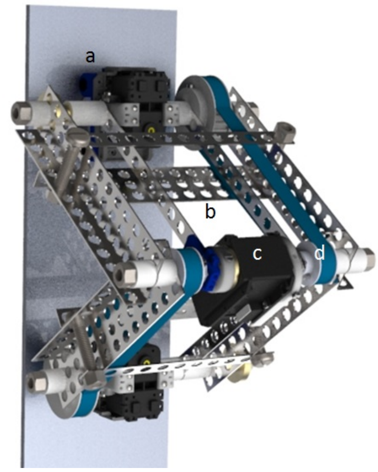

Fig. 1. InchwormClimber: a- Adhesion Unit with actuator, b- transverse bar, c- climbing mechanism actuator, d- pulley and belt.

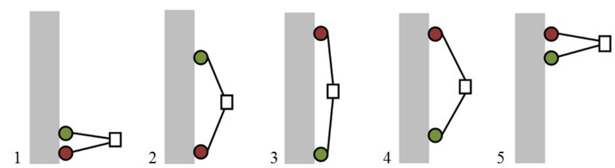

Fig. 2. InchwormClimber locomotion (red indicates the adhesion units magnet is on, providing maximum adhesion force, while green means its off): 1- Beginning of step, the robot is at minimum extension, 2- the climbing mechanism actuator drives the links in order to depart from each other, 3- the robot reaches its maximum extension, the adhesion units change their status in turn 4- the climbing mechanism actuator turns in an opposite direction and the links approach each other, 5- the robot is again at minimum extension.

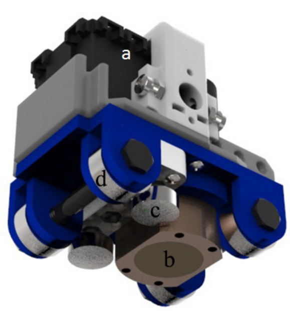

Fig. 3. Adhesion unit: a- AX-12 actuator, b- switchable magnet, c- permanent magnet, d- bearing.

While there are many types and configurations of switchable magnets, they all obey to the same principle of redirecting and changing the path of the magnetic flux. Here we will use an H-type switchable magnet device which was patented by Perry J Underwood and Franz Kocijan[24]. A H-type unit is composed of two cylindrical permanent magnets encircled in a ferromagnetic chamber. Both magnets are magnetized diametrically. One magnet is fixed and the other one is moving. When rotating the moving magnet for 180^o, the magnetic flux is closed between the magnets and almost no flux is transmitted to the contacting object and in this way the device will apply almost no adhesion force. The geometry of the chamber around the magnets has an important role in directing the lateral magnetic fluxes and in maximizing the force when the device is on and minimizing the force when the device is off.

In order to minimize the power consumption due to friction, the adhesion unit is designed with a rolling motion rather than sliding motion. While moving, the adhesion force should be just enough to maintain the adhesion unit attached so that the rolling movement exerts very little friction force against the movement direction. This way we reduce the required torque and power of the climbing mechanism actuator. However, at static position a higher normal force is required in order to keep the unit firmly attached to the structure and support the forces and torques from the whole structure.

A novel small scale switchable magnet unit, shown in Fig. 5, was developed and optimized for this and other small robotic applications, regarding the following criteria:

- High adhesion force to mass ratio;
- Provide adhesion force on ferromagnetic structures with the material thickness of as low as 1*mm*;
- Device with lower profile (lower height to reduce the detaching torque and withstand higher suspended weight) as depicted in Fig. 6;
- Zero power consumption at any state;
- Ability to control the force;

We started by making simulations with *Comsol Multiphysics*, a physics simulation software, to better understand the working principles of switchable magnets and the effect of different design and material parameters on the attraction force of the unit.

A thick iron housing around the magnets is useful for directing all magnetic flux of the permanent magnets and increasing the holding force. However, if the climbing surface is not very thick, some percentage of the flux is not useful for generating the holding force, as depicted on Fig. 4. Therefore the thickness of the housing should be optimized in relation to the typical thickness of the structures that should be climbed. Therefore, by making simulation in *Comsol*, we analyzed the magnetic fluxes for several housing designs and optimized its geometry.

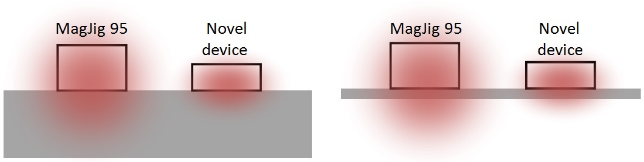

Fig. 4. Comparison between the magnetic field of the MagJig 95 and of the novel device in plates with different thickness

The developed switchable magnet unit, depicted in Fig. 5, is $\phi 28x22mm$ and can apply a force of 56N in a 1mm steel plate and 100N on a 3mm steel plate.

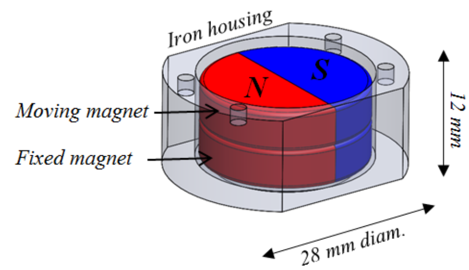

Fig. 5. Novel optimized switchable magnet unit.

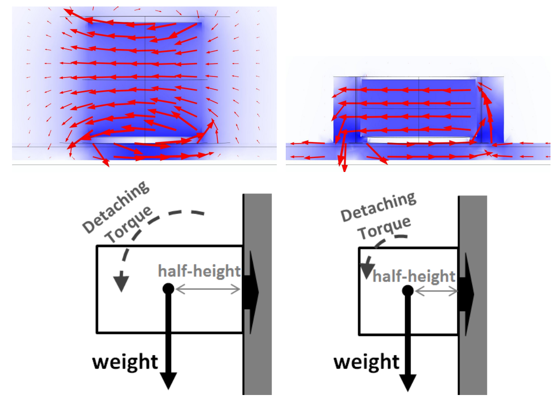

Fig. 6. Above: Simulations in *Comsol Multiphysics*. Below: Reduction of the detaching torque with a lower profile.

The integrated actuator is a *Bioloid AX-12* actuator which is able to actuate the unit, Furthermore, the inertia of the actuator is enough to maintain the position of the rotating magnet of the magnetic unit at any position. In this way we guarantee that the switchable magnet unit can stay at any of its status without consuming power. It is important to be able to control the adhesion force in order to fine-tune the force for different ferromagnetic structures due to the variations on the thickness and the materials. We made simulations in *Comsol* and also experiments in order to measure the adhesion force of the switchable magnet based on different actuator positions (i.e. the relative position between the diametrically magnetized permanent magnets) and then used a nonlinear regression to find a function that estimates the holding force depending on the actuator position which is presented in Fig. 7. The values on the *Comsol* simulation closely follow the experimental results. We found out that a polynomial of the fourth degree can estimate the adhesion force with the mean square error of 0.9962:

$$F = -2^{-7}\theta^4 + 0.0001\theta^3 - 0.0219\theta^2 - 0.1607\theta + 186.3 \quad (1)$$

Where:

- F is the attraction force;
- θ is the angle between the magnets.

C. The Climbing Mechanism

As can be seen in Fig. 8, the climbing mechanism is composed of 2 links and 3 revolute joints that are actuated by

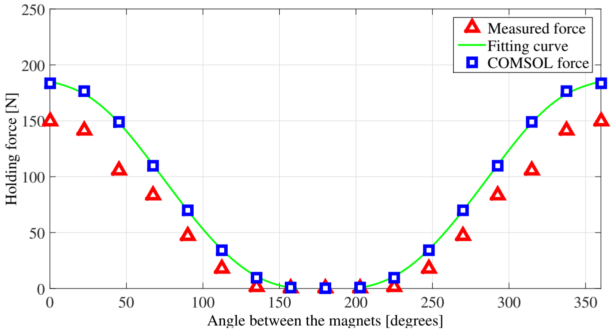

Fig. 7. Variation of the holding force according to the moving magnet's angle.

a single actuator placed in the middle joint. The motion is transferred to the other two joints with a belt and pulley system. The ratio of motion transfer is 2:1, required to maintain both of the adhesion units parallel to the surface.

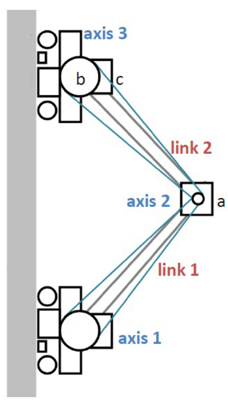

Fig. 8. Side view schematics: a- Climbing mechanism actuator, b- Pulley, c- Adhesion unit.

To descend, the robot can simply use gravity. To control the descending velocity, one can increase the friction by increasing the magnetic force of the adhesion units.

III. System Kinematics and Dynamics

We can identify and define the several design parameters of the robot to determine the system kinematic and dynamic model. Let us consider:

- T as the torque $[N.m]$;
- l as the length $[m]$;
- r as the pulley radius $[m]$;
- W as the weight $[N]$;
- F_f as the friction $[N]$;
- P as the power $[W]$;
- ω as the angular velocity $[rad/s]$.
- $_M$ stands for motor;
- $_{sp}$ stands for smaller pulley;
- $_{bp}$ stands for bigger pulley;
- $_{au}$ stands for adhesion unit.

Fig. 9 depicts all external forces applied to the robot. Based on this diagram, we can estimate the required torque on each axis:

$$T_{axis1} = l_{link} \times (W_M + 2 \times W_{sp} + W_{link}) \tag{2}$$

$$T_{axis2} = l_{link} \times (W_{au} + W_{bp} + F_f + \frac{W_{link}}{2}) \tag{3}$$

$$T_{axis3} = 0 \times (W_{au} + W_{bp} + F_f) \tag{4}$$

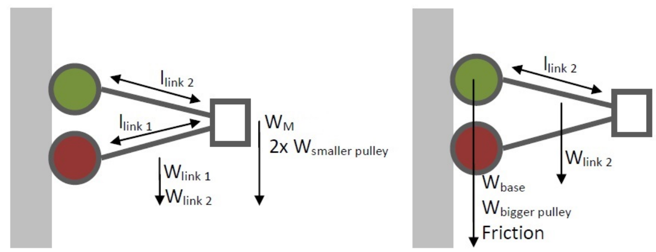

Fig. 9. Free body diagram.

The pulleys on the magnets have to move half the velocity of the opening of the links, therefore:

$$r_{bp} = 2r_{sp} \tag{5}$$

Because the joints move at different velocities, we need to make a formulation based on the mechanical power needed on each joint. The belt has the same velocity v in all points, so we can use it to relate the angular velocities.

$$P_{axis1} = T_{axis1} \times \omega_{axis1} = T_{axis1} \times \frac{\omega_M}{2} \tag{6}$$

$$P_{axis2} = T_{axis2} \times \omega_{axis2} = T_{axis2} \times \omega_M \tag{7}$$

$$P_{axis3} = T_{axis3} \times \omega_{axis3} = 0 \times \omega_M = 0 \tag{8}$$

The total power required corresponds to the sum of the power to each axis:

$$P_M = P_1 + P_2 + P_3 = T_M \times \omega_M \tag{9}$$

$$T_M = l_{link} \times (\frac{W_M}{2} + W_{sp} + W_{au} + W_{bp} + F_f + W_{link}) \tag{10}$$

The friction force between a ferromagnetic surface and the adhesion unit was estimated by experimental results by sliding the adhesion unit on the surface, while keeping the switchable magnet off. We considered each link length equal to $15cm$ to guarantee each step of about $20cm$. Based on these required power and torque, we selected the actuator from the *Bioloid Dynamixel* series motor, the *MX-64* actuator. It has a stall torque of $6.4Nm$, so we can run it at nominal torque of $3.2Nm$, with a safety factor of 2, since our required torque is equal to $1.60Nm$.

IV. System Integration

The robot integrates two *AX-12* actuator from the dynamixel series [25] to activate the magnets on the adhesion units and a *Dynamixel MX-64* to drive the links. A CX-530 Controller is used to control the motor gaits. The total mass of the robot is $675g$ (without batteries) and each step (distance it moves during a cycle) is about $22cm$. The foot print of the Inchwormclimber is only $38mm$, so this robot can climb narrow structures with a width of as low as $40mm$.

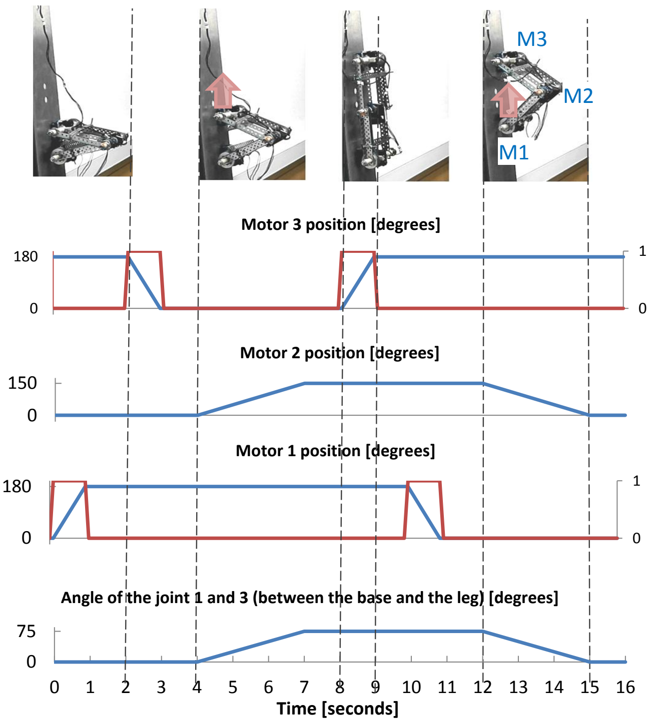

Fig. 10. Motor gaits and joint positions during a full climbing cycle. Blue shows the motor position and red shows the power input to the motor. As can be seen the power input to switchable magnet units is only during switching action

We could successfully test the robot climbing and descending a ferromagnetic structure which is presented in Fig. 11 and the multimedia extension. The experiments were made on 3 structures with 1, 2 and 3 mm of plate thickness. In all instances, with a simple adjustment on the adhesion force of the adhesion unit, the robot could successfully climb and descend the structures. The adjustment is basically changing the AX-12 actuator gait in order to fine-tune the minimum and maximum adhesion force. Fig. 10 shows an example of motor gaits and joint position during execution of one cycle.

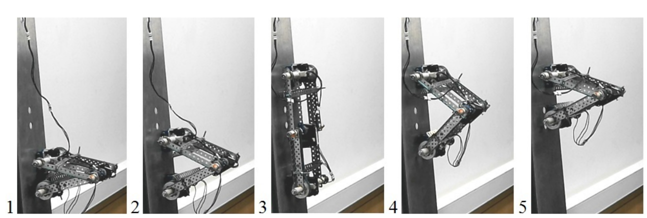

Fig. 11. InchwormClimber climbing during experiments.

A. Power Consumption and Autonomy

In this section, we calculate the power consumption of the InchwormClimber. Also, we assume an additional mass of $250g$ for the battery, which will constitute 27% of the whole robot's weight and will calculate the power autonomy with such a battery to present an idea of the autonomy of such system.

First, we need to figure out the energy consumption per cycle. The power of each motor can be calculated as the product of the voltage of the motor and the mean current intensity during its activation. Then, the energy consumed is equal to the power consumed times the total time during which, each motor is activated during a cycle.

We consider that both motors use their maximum power at each cycle. If such power is multiplied by their activation time in each cycle, the total energy of each cycle can be calculated. This can be seen in the Table I. At the highest power rate, the switchable magnet actuator could switch the magnet at $0.5s$. However, for the arm motor (MX-64), the motor could safely rotate at around 9 RPM without overheating (compared to 60 RPM maximum at no load). Therefore the movement took around 3 seconds at maximum power. Table I shows the energy consumption during each cycle for each of the motors. The total power consumption per each cycle is 2x(144+5)=298J.

TABLE I

Energy consumption during one cycle

	AX-12 (adhesion unit)	RX-64 (arm unit)
Max power	10 W	48 W
Engagment duration per cycle	0.5 s	3 s
Total energy per cycle	5 J	144 J

As an example for the autonomy of the robot, we can consider the battery in the *Bioloid* kit that is a 3 cell Li-PO battery and can supply $11.1V$ to drive the *AX-12* and *MX-64* motors. It has a capacity of $1000mAh$ (1Ah) and has a mass of $83g$. Three of these batteries have a mass of $249g$, and provide a capacity of $3AH$. The total stored energy on these batteries can be calculated as:

$$Total\ energy = 3 \times 3600(s) \times 11.1(V) = 119880J \quad (11)$$

This provides the robot a total of 402 cycles, which is equal to $88.4m$ of climbing (based on $0.22m$ climbing steps at each cycle).

B. Comparison with an Electromagnet Unit

An electromagnet unit that can apply approximately the same force of the switchable magnet can be found in [26]. Table II shows the comparison between the electromagnet unit and the developed switchable magnet unit with the actuator. As can be seen the switchable magnet unit is lighter and can apply a higher force. Furthermore, the switchable magnet is less sensitive to the distance and consumes energy only on switching action.

TABLE II
COMPARISON BETWEEN THE ELECTROMAGNET AND THE SWITCHABLE MAGNET DEVICE

	Electromagnet	SM*	Variation
Mass [g]	108	97.1	-10%
Holding force [N] (1 mm steel)	45	56.5	+26%
Force/Mass ratio [N/g]	0.42	0.58	+39%

*Switchable Magnet with actuator

V. CONCLUSIONS

In this article we presented the design and implementation of the *InchwormClimber* robot based on a switchable magnet adhesion unit with rolling motion. The switchable magnet was optimized for the application of climbing robots on ferromagnetic structures with up to 1*mm* thickness. The switchable magnet consumes energy only in case of switching, thus being advantageous in comparision with electromagnets. With an overall weight of 1kg including batteries, the robot will have enough autonomy to climb 88m on ferromagnetic structures.

Another advantage of the *InchwormClimber* is its small foot print that would allow it to climb very narrow structures. The robot is relatively light-weight and can achieve large climbing steps. Furthermore, the ability to control the adhesion force based on the actuator position, would allow us to fine tune the adhesion force based on the material and thickness of the structure which should be climbed.

Future works includes further optimization of the robot in terms of weight reduction, generation of optimal motion gaits for a fast climbing movement and test of the robot on different structures, i.e. curved structures.

VI. ACKNOWLEDGMENT

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