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ORION-II: A Miniature Climbing Robot with Bilayer Compliant Tape for Autonomous Intelligent Surveillance and Reconnaissance

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Abstract— **This paper presents the design and fabrication of ORION-II for autonomous Intelligence, Surveillance and Reconnaissance (ISR). ORION-II is a miniature climbing robot equipped with all the necessary electronic components to achieve ISR tasks. It consists of a robot chassis (tail) carrying the electronics and two DC motors each driving a wheel-leg (wheg) with four "flaps" equipped with bilayer compliant tapes. Two types of tapes are used for attachment of ORION-II: bilayer PDMS/foam and bilayer micro-suction/foam. The two types of tapes are tested on different climbing surfaces, and the climbing performance is reported. ORION-II could climb rougher surfaces when using the PDMS/foam tape, and perform internal climbing transitions when using the micro-suction/foam tape. The total weight of ORION-II is 153.18 g as compared with 71.5 g of our previous version ORION-I.**

I. INTRODUCTION

The use of robots for autonomous intelligence, surveillance and reconnaissance (ISR) requires mapping, monitoring, detection and tracking. These tasks require many electronic components which increase the weight of the robot. While weight is an important factor for miniature climbing robots, our aim in this paper is to design a new version of ORION [1], called ORION-II equipped with all the necessary electronic components to achieve ISR tasks. ORION is a miniature climbing robot using compliant tapes attached on wheel-legs (whegs) for climbing.

ORION-I [1] used polydimethylsiloxane (PDMS) dry adhesive tapes attached on the four "flaps" wheel-leg (wheg) of the robot to climb. Our own developed PDMS dry adhesive is characterized by a high shear adhesion force and a low normal adhesion force which limits the climbing angle of ORION-I to 110° after which the normal force begins to play an important role in climbing. Climbing vertically up of 90° is becoming more challenging now with ORION-II using our PDMS dry adhesive, and especially because ORION-II is expected to be much heavier than ORION-I with the addition of all the necessary electronic components to achieve ISR tasks. While our requirement was not to climb above 90°, having a low normal adhesion force has the advantage of decreasing the torque required to peel-off the sticky PDMS tape from the climbing surface. On the other hand, it limits the climbing performance of the robot and prevents it from climbing upside down on a ceiling for example. Given the limitation in our own developed PDMS dry adhesive, and to increase the climbing performance of the robot for 360° and achieve climbing inverted on ceiling, a compliant tape with high normal adhesion force must be used. A commercially available micro-suction tape from Sewell Inc. with high normal adhesion force to overcome the drawback of our PDMS dry adhesive is chosen to improve the climbing performance of ORION. It has the advantage of PDMS dry adhesive in terms of durability and reusability, and like dry adhesives, it leaves no residue on the climbing surface. The use of this micro-suction tape will require high torque motors to lift it off the climbing surface. This is therefore considered in our design of ORION-II. It is expected that the micro-suction tape will allow ORION to climb higher inclination angles. On the other hand, because of its micropillar, the PDMS dry adhesive is supposed to work better on rougher climbing surfaces.

Other than PDMS dry adhesion and micro-suction, different attachments are used in the literature for climbing robots. Tache et al in [2] used magnetic attachment for climbing. Magnets are strong but only work on ferrous surfaces. Prahlad et al. in [3] used electro-adhesive attachment for climbing. This requires high voltage in the order of kV. Xiao et al. in [4] used vacuum suction attachment for climbing. Suctions require bulky compressed air and completely smooth surfaces to establish an ideal seal. Sintov et al. in [5] used gripping attachment for climbing. Gripping does not work on smooth surfaces and requires looking for randomly-located handholds. Dry adhesive like PDMS or micro-suction tape can potentially overcome those drawbacks. They are light weight, power efficient, passive, operationally quiet, and can climb independent of the surface material. Dry adhesion like our home developed PDMS is proposed in [6]–[10] for climbing robots. Micro-suction tape is used for a climbing robot in [11] and it showed promising results.

ORION locomotion mechanism is like the Mini-Whegs robot locomotion in [12] and the Waalbot robot locomotion in [13]. Mini-Whegs is very small which makes it impractical for ISR tasks. Waalbot does not have compliant tape for attachment on climbing surfaces, making floor-to-wall, wall-to-floor or wall-to-ceiling transitions very complicated. ORION has a weight of 153.18 g to include all the required electronics for ISR tasks and still able to climb vertically up using PDMS dry adhesive, and making internal transitions using micro-suction tape.

In this paper, we will introduce ORION-II, then we explain

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the bilayer compliant tape concept of ORION. We will describe the design and fabrication of ORION-II, and end by testing ORION-II on different climbing surfaces and evaluate its climbing performance before concluding at the end.

II. The Climbing Robot: ORION-II

The architecture of ORION-II in Fig. 1 is similar to ORION-I presented in [1] where it consists of a robot chassis (tail) carrying the electronics and two DC motors each driving a wheel-leg (wheg) with four "flaps" equipped with sticky tapes. There is a 4:1 gear reduction between the motor and the whegs. The only difference with ORION-I is in the geometry of the robot. Here, we are using a bigger chassis and wider whegs to support more electronic components and a heavier robot's weight. ORION-II weighs 153.18 g as compared with 71.5 g of ORION-I. Also, in this new version, the whegs are closer to the centre of mass. This helps in supporting a heavier robot's weight.

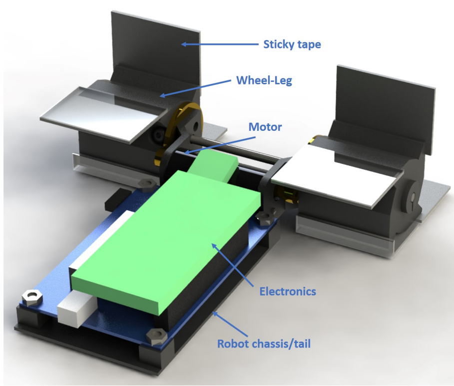


Fig. 1: CAD model of miniature climbing robot with wheel-leg configuration of four "flaps"

The sticky tapes used here to evaluate the robots performance are PDMS and micro-suction tapes. The characteristics of both tapes are given in Table I. The main difference in characteristics between them is the normal adhesion as shown in Table I.

PDMS tape	Micro-Suction tape
In house fabrication [1]	Commercially available [14]
Durable and reusable	Durable and reusable
Low normal adhesion	High normal adhesion
High shear adhesion	High shear adhesion

TABLE I: Characteristics of PDMS and Micro-suction Tapes

The PDMS tape used is a patterned micropillar dry adhesive produced at our laboratory [1]. Fig. 2 shows the PDMS when demolded from a master mold after curing. The resulting structures were pillars with 2 μm diameter, 2 μm height, and 6 μm center-to-center spacing in a hexagonal distribution (Fig. 2). The patterns were distributed as a square of area 1 cm^2, and each square patch has a distance of approximately 1 cm^2 between each other. Hence an adhesive flap of 10 cm^2 has 5 cm^2 area with these patterns and the rest of the area is unpatterned.

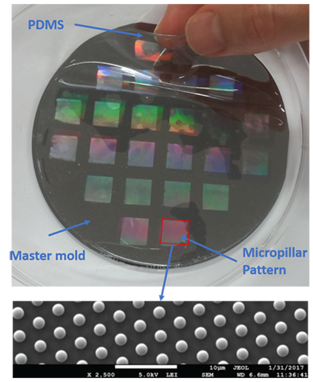


Fig. 2: PDMS tape as final product when demolded from a master mold

The micro-suction tape used is a commercially available tape [14] with thousands of microscopic craters in its surface, functions like micro-suction cups, and works by creating many partial vacuums between the tape and the surface.

III. Bilayer Compliant Tapes

The adhesive tape is ORION's essential attachment on the climbing surfaces. Although compliant adhesive tape is a must for the ORION architecture to climb, the normal adhesion force plays a critical role in increasing the climbing robot's performance. It was observed from various reports in the literature that the addition of a foam backing layer enhances the adhesive force of PDMS [16], [17]. In order to verify this observation on our PDMS, a test apparatus to measure the adhesion (normal) force of PDMS is shown in Fig. 3. The setup consists of a CNC milling machine, a digital balance with a range of $+/-$ 300 g and a precision of 0.01 g, and an acrylic piece of 25 mm $\times$ 25 mm was attached to the drill chuck of the CNC milling machine to simulate the climbing wall.

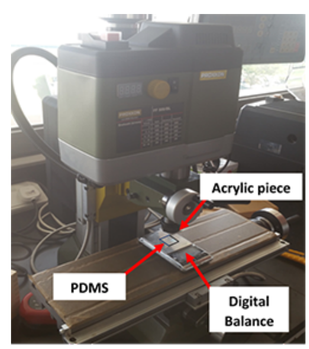
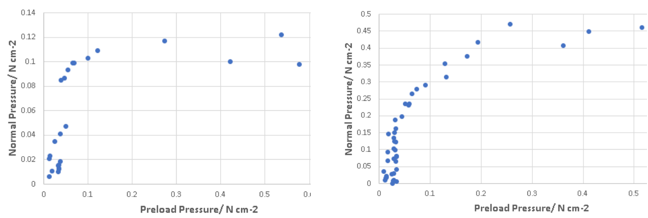


Fig. 3: A CNC milling machine for measuring the normal force of the PDMS

The viscoelastic foam core of the 3M VHB tape absorbs the tensile stress, spreads the stress throughout the entire bond, imparts equal load sharing, and possesses high internal cohesive strength [15]. For these reasons, the 3M Scotch VHB tape 4607 is chosen as a backing layer for the PDMS.

Two tests are realized. In the first test, a PDMS specimen (20 mm $\times$ 20 mm $\times$ 0.5 mm) without backing layer was taped, using a very thin double-sided tape onto the centre of the weighing pan of the balance. In the second test, the PDMS specimen with backing layer of 3M VHB double side tape was taped directly onto the centre of the weighing pan of the balance. In both tests, the acrylic piece was used to apply preload ranging from 2 g to 250 g on the PDMS specimen. Each test commenced with preloading the PDMS specimen by rotating the vertical feed handwheel of the CNC machine to lower the acrylic piece. The preload was indicated by the positive balance reading. Once the balance reading reached the desired value, the acrylic piece was withdrawn. The negative balance reading during the withdrawal represented the normal adhesive force on the PDMS specimen.

The preload and normal adhesive force are normalised over the area to give preload pressure and normal pressure respectively. The results for the experiment on PDMS with and without foam backing layer are shown in Fig. 4

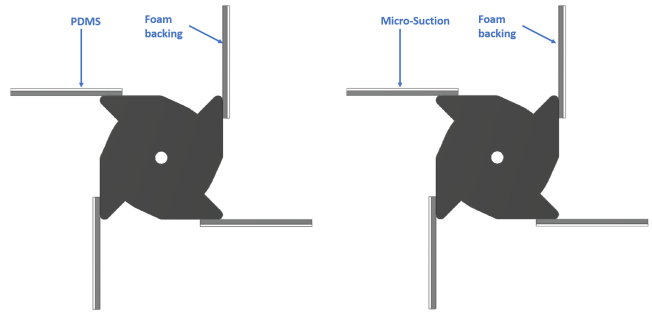


(a) (b)

Fig. 4: Normal Pressure versus Preload Pressure for a bilayer foot material (a) PDMS without foam backing layer, (b) PDMS with foam backing layer

Both graphs show that as the preload pressure increases, the normal pressure increases at a decreasing rate. The maximum normal pressure is 0.14 N/cm for PDMS without foam backing layer while it is 0.71 N/cm for PDMS with backing. The graph of PDMS with backing is also significantly higher than the graph of PDMS without backing. This shows that the application of foam backing increases the normal adhesive force of PDMS on acrylic surface, and this is compatible with literature finding [16], [17].

Due to the small range of the digital balance used in our setup, the adhesion performance of the micro-suction tape could not be measured. However, it has been shown experimentally that the micro-suction tape will perform better on climbing robot when a foam backing layer is added to it. Therefore, the PDMS and the micro-suction foot materials are bonded on the 3M Scotch VHB tape 4607 (foam backing), forming a composite bilayer sticky tape, which is being used in the climbing robot as the attachment mechanism onto the climbing surfaces (Fig. 5).



(a) (b)

Fig. 5: Composite bilayer compliant tape attached to the robot's wheel-leg (a) PDMS with foam backing layer, (b) Micro-Suction with foam backing layer

IV. Design and Fabrication of ORION-II

Two main design goals are required for ORION-II. The first is to achieve up to 110° climbing angle using PDMS dry adhesive with foam backing layer (like ORION-I goal), and the second is to increase the performance of the robot by using micro-suction tape with foam backing layer. In [1], the quasi static model of ORION is developed where a free body diagram of it is presented and used to analyse the required adhesion force. A slider-crank model of the robot is used to simulate the changes in robot parameters required to calculate the adhesive force as the robot is in motion. Thereafter, the minimum required adhesive force for climbing different slope angle is generated and used to define the adhesive design requirement (adhesion area needed). And last, the minimum required motor torque needed to select the required motor is calculated. Based on the quasi static model, our design goal for ORION-I in [1] was to determine the required adhesion area and the required motor torque to achieve climbing up to 110°, and therefore secure climbing vertically up (90°) using PDMS dry adhesive with foam backing layer, and this is for a given robot's geometry and weight. Having the same design goal here in this paper for ORION-II, where for a given ORION-II geometry and weight, the robot is required to climb up to 110° using PDMS dry adhesive with foam backing layer. This time, the problem is more challenging given that ORION-II must be equipped with all the electronic components required to achieve ISR tasks, and therefore an increase in robot's weight is expected.

A. Electronics Hardware for ISR

The electronic hardware of the robot required to achieve ISR tasks is divided into 2 layers called high level layer and low lever layer. The high-level term is in the sense that the layer will perform the high computationally required tasks such as path planning, map construction, computer vision etc. The low-level will manage sensors, actuator and power. Furthermore, the low-level will control some robot behaviors which require fast response in millisecond such as dynamic control, obstacle avoidance and waypoint navigation. The two layers will communicate through UART serial connection. The low-level layer will constantly send the sensors data and robot's state to the high-level, meanwhile the high-level will process the data and return instructions to the low-level. The high-level layer includes 1 microcontroller Raspberry Pi Zero, 1 Pi camera 8 megapixels and 1 X-bee communication module. The low-level consists of 1 microprocessor Arm-Cortex M4 STM32F411, 1 IMU 9-axis Bosh BNO55, 1 ranging sensor array, 1 UWB module for localization [18], 1 motor driver which controls 2 high-quality Faulhaber motors and 1 battery management circuit. In addition, the robot is equipped with a wireless charger module and it communicates with other robots using XBee module. It is powered by a 3.7V 850mAh Li-Po battery 703040P. Fig. 6 shows the electronic components needed to achieve ISR tasks. The total weight of the electronic components is about 67 g.

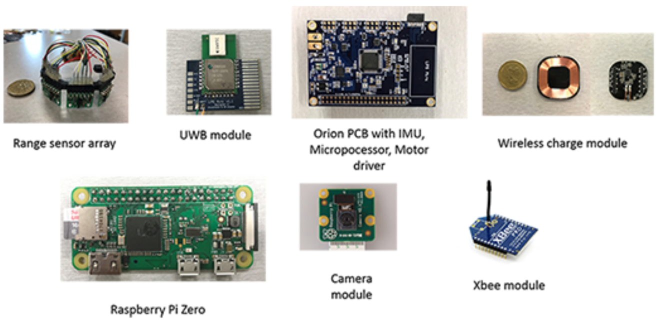


Fig. 6: Electronic components needed for ISR tasks

B. Prototyping

Based on our previous analysis in [1], the length of the robot chassis (tail) is proportional to the normal force. Therefore, increasing this length will help in supporting a higher angle of inclination. The electronics components are therefore assembled along the length of the robot in a total square area of 109.32 mm $\times$ 46 mm. A total chassis (tail) length of 109.32 mm for ORION-II is considered in comparison to 74.32 mm chassis length for ORION-I. Although, the effect of the robot's width is not considered in our previous analysis [1], the experimental tests on ORION-I show that by having the whegs closer to the centre of mass of the robot, the climbing angle will increase. Therefore, in the design of ORION-II, the adhesions are taken closer to the centre of mass, and a rectangle chassis of total width of 46 mm is considered instead of 60 mm width (length of the large trapezoidal base) in ORION-I.

In addition to the design goal of climbing up to 110° using PDMS dry adhesive with foam backing layer, our second design goal is to overcome the limitation of our own developed PDMS dry adhesive by replacing it with micro-suction tape, enhancing the climbing performance of ORION on high inclination angle. The micro-suction tape is characterized by high normal adhesion force, and therefore requires high motor torque to peel it off. In the design of ORION-II, in addition to the motor selection, the 3D printed plastic gears between the motor and the wheg are replaced by metal gears to prevent braking due to the high torque. This will add an additional 30 g weight to the total weight of the ORION-II. Fig. 7 shows a comparison between ORION-I and ORION-II prototypes without the whegs.

ORION-I has a weight of 54.5 g without electronics. If ORION-II and ORION-I have the same 3D printed weight, the total weight of ORION-II is therefore 151.5 g (54.5 (3D printed parts) + 67 (electronic components) + 30 g (metal gears)). Considering a fixed wheg radius for ORION-II like ORION-I (19.37 mm), in consequence, to avoid overlapping of the adhesives (sticky tapes) on each other, the maximum length of the adhesive should not exceed 20 mm for a wheg radius of 19.37 mm. The width of the adhesive is calculated in the next subsection IV-C from the minimum required adhesion area, and the wheg width is therefore determined.

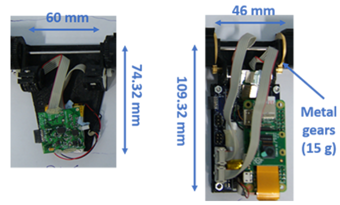


Fig. 7: ORION prototypes without whegs: ORION-I (left), ORION-II (right)

C. Compliant Tapes' Size

For ORION-I, and based on our developed quasi static model and the adhesion performance of the PDMS extracted from the literature [19] a minimum PDMS adhesive area of 5 cm^2 per flap is required to be able to climb up to 110° slope angle. Experimentally, it was found that the robot could climb a 110° slope with a minimum adhesive area of 7 cm^2 per flap, thus a wheg width equals to the adhesive width of 35 mm (considering a maximum adhesive length of 20 mm).

In this paper, for ORION-II, the adhesion performance of the PDMS with foam backing layer that we use is obtained here from Fig. 4b and not extracted from literature as in ORION-I in [1]. This will help in determining more accurate adhesion area. The curve of Fig. 4b can be approximated by a power law function [20] $P_A = 0.675 P_P^{\frac{1}{2.4}}$ where P_A is the adhesion pressure, and P_P is the preload pressure.

In order to identify the suitable size of the adhesive material, the adhesion vs preload curve (Fig. 4b) is overlayed with lines of gradient values corresponding to the inverse of the preload-to-peeling ratio at various climbing slope angle θ (detailed description in [1]). This is shown in Fig. 8 for some slope angles.

The intersection of the performance curve and this inverse-ratio line then gives the specific preload pressure $P_P{}^*$ used to calculate the adhesion area. The minimum required adhesive area (A_a) is then obtained by

$$A_a = \frac{F_{Fn}}{P_P{}^*} \qquad (1)$$

where F_{Fn} is the critical peeling force and equal to 0.55 N for 110° slope angle. F_{Fn} is obtained using the same procedure in [1]. Based on this analysis, our robot requires a minimum adhesive area of 8.8 cm^2 per flap to be able to climb up to 110° slope angle. ORION-II is using two high torque DC motors at 14.85 mNm each (Faulhaber 1512U003SR 112:1 running at 75% continuous torque capacity). The selection of the motor is also guided by the use of micro-suction tapes. The micro-suction tape is characterized by high normal adhesion force, and therefore it requires a high torque to

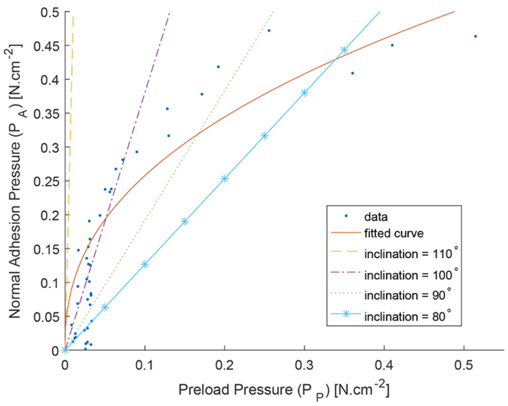


Fig. 8: Adhesive performance curve overlayed with lines of gradient values of the inverse of the preload-to-peeling ratio for several slope angles.

peel it off from the climbing surfaces. In addition, when using micro-suction tape, the robot is expected to climb all the inclination angles and performs internal transition. This requires a high torque motor to balance the robot when climbing inverted on ceiling or climbing vertically down. A useful analysis and discussion on torque requirement and motor selection could be found in [1].

Experimentally, it was found that the robot could climb a 110° slope with a minimum adhesive area of 8.6 cm^2 per flap using PDMS with foam backing layer, and therefore a wheg width equal to the adhesive width of 43 mm (considering a maximum adhesive length of 20 mm). This result is very close to the adhesion area obtained in simulation (8.8 cm^2).

In the absence of the adhesion performance of the micro-suction tape due to the small range of the digital balance used in our setup (Section III), the minimum required area to climb all the inclination angles (360°) using micro-suction tape with foam backing layer is optimized experimentally by trials and errors. It was found that the robot could climb all the inclination angles and performs internal transition with a minimum adhesive area of 4 cm^2 per flap (20 mm × 20 mm) using micro-suction tape with foam backing layer.

The total weight of ORION-II is 153.18 g as compared with 71.5 g of ORION-I. Videos of ORION-II demonstrate climbing at an angle of 110° using the bilayer PDMS and an internal transition while using the bilayer micro-suction tape can by found in the youtube link.

V. Testing and Results

In this section, we will test the PDMS and the micro-suction tapes on different climbing surfaces with 90° inclination angle, then we will analyse the climbing performance of the robot on a given climbing surface.

A. Different climbing surfaces

PDMS and micro-suction tape were tested on different surfaces to compare its ability to climb. The different test surfaces are acrylic, glass, whiteboard, metal lift door, wooden door, smooth wood and painted concrete wall. Fig. 9 shows some of the climbing surfaces.

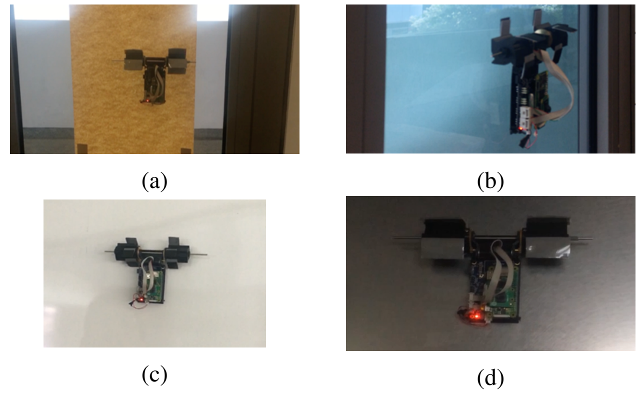


Fig. 9: Different climbing surfaces: (a) Acrylic, (b) Glass, (c) Whiteboard, (d) Metal lift door

PDMS and micro-suction both performed well on the smooth surfaces such as acrylic, glass and whiteboard but both failed on rougher surfaces. However, PDMS has a slight edge over micro-suction where it was still able to climb on certain metal surfaces. A summary can be found in Table II

PDMS	Test surface	Micro-suction
Success	Acrylic	Success
Success	Glass	Success
Success	Whiteboard	Success
Success	Smooth Metal (Lift)	Fail
Fail	Smooth Wood	Fail
Fail	Wooden door	Fail
Fail	Painted Concrete Wall	Fail

TABLE II: Climbing ability for different surfaces

To improve the climbing ability of micro-suction tape, the surface area was increased to the same surface area as PDMS (43 mm × 20 mm) and the tests were repeated. However, there were no changes with micro-suction still failing to climb smooth metal. Videos showing the climbing on different surfaces for both PDMS and micro-suction tape are given in the multimedia attachments.

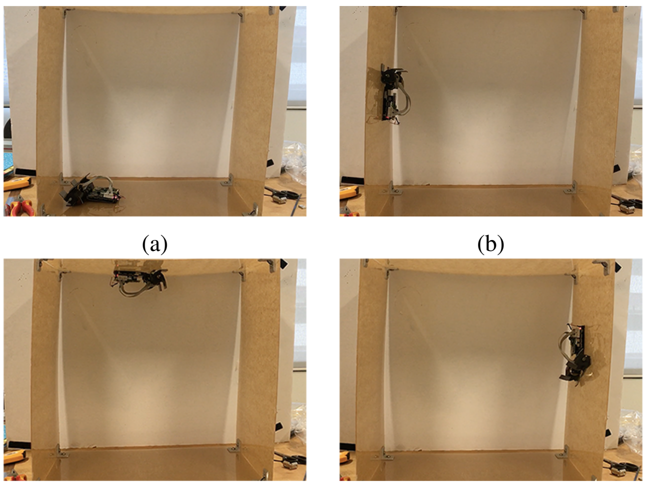
B. Climbing performance (PDMS vs Micro-Suction)

The test environment was a smooth, clean acrylic at room temperature (about 22°C). The robot climbed up the vertical acrylic repeatedly with both adhesives (PDMS and micro-duction). The tests were performed with increasing inclination until maximum is attained.

1) Adhesive performance: The PDMS is first mounted on "3M Scotch VHB 4607" tape before attaching it to the wheg. It was able to peel off the surface of the acrylic with ease because it requires very low peeling force. The feet adhere well to the surface of the acrylic. With continuous testing, the PDMS started to bend and this reduces the effective contact area between the PDMS and the acrylic and had to be constantly changed to a new piece. Besides that, dust will get stuck on the PDMS and this also reduces its effectiveness.

Micro-suction tape is first mounted on "3M Scotch VHB 4607" tape before attaching it to the wheg. However, the tape was not sturdy enough and a small piece of clear plastic sheet was added in between to provide more support and rigidity. The micro-suction tape has very high adhesion and hence a high torque is required. The area of the micro-suction was reduced to an optimal size for climbing. Micro-suction tape is more resistant to dust and impurities on the tape.

2) ORION-II performance: With PDMS, the robot was only able to climb up the acrylic easily to about 110°. Since the adhesive requires low torque to peel off the surface, the robot has an average speed of about 4.45 cm/s vertically up. With micro-suction, the robot was able to climb the acrylic in all inclination angles with a slower average speed of 3.44 cm/s vertically up. Fig. 10 shows ORION-II with internal transitions capabilities. A video showing the internal transition with micro-suction tape on acrylic surface is provided in the multimedia attachments. Table III summarizes the climbing performance of ORION-II for PDMS and micro-suction tape.



(a) (b) (c) (d)

Fig. 10: ORION-II with internal transitions capabilities: (a) Horizontal, (b) Vertical-up, (c) Inverted, (d) Vertical-down

Type of tape	Vertical travel speed (cm/s)	Maximum incline
PDMS	4.45	120
Micro-suction	3.44	360

TABLE III: ORION-II climbing performance for PDMS and Micro-Suction tape

VI. Conclusion and Future Work

In this paper, the design and fabrication of a miniature climbing robot equipped with all the necessary electronic components to achieve Intelligence, Surveillance and Reconnaissance (ISR) tasks are presented. The robot is called ORION-II as a second version of our ORION-I, where two types of tapes are used for attachment onto the climbing surfaces. Different climbing surfaces are tested using PDMS/foam and micro-suction/foam tapes, and the climbing performance is reported. ORION-II could climb rougher surfaces when using the PDMS/foam tape, and perform internal climbing transitions when using the micro-suction/foam tape. The design will be improved in the future to achieve further miniaturization, external transitions and steering capability.

References

[1] A. G. Dharmawan, P. Xavier, D. Anderson, K. B. Perez, H. H. Hariri, G. S. Soh, A. Baji, R. Bouffanais, S. Foong, H. Y. Lee, and K. L. Wood, "A Bio-Inspired Miniature Climbing Robot with Bilayer Dry Adhesives: Design, Modeling, and Experimentation," in *Proc. ASME Int. Des. Eng. Tech. Conf. Comput. Inform. Eng. Conf. (IDETC/CIE)*, in press, 2018.

[2] F. Tâche, W. Fischer, R. Siegwart, R. Moser, and F. Mondada, "Compact magnetic wheeled robot with high mobility for inspecting complex shaped pipe structures," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, pp. 261-266, 2007.

[3] H. Prahlad, R. Pelrine, S. Stanford, J. Marlow, and R. Kornbluh, "Electroadhesive robotswall climbing robots enabled by a novel, robust, and electrically controllable adhesion technology," in *Proc. IEEE Int. Conf. Robot. Autom.*, pp. 3028-3033, 2008.

[4] J. Xiao, W. Morris, N. Chakravarthy, and A. Calle, "City climber: a new generation of mobile robot with wall-climbing capability," *Unmanned Syst. Technol. VIII*, pp. 62301D, 2006.

[5] A. Sintov, T. Avramovich, and A. Shapiro, "Design and motion planning of an autonomous climbing robot with claws," *Robot. Auton. Syst.*, vol. 59, no. 11, pp. 1008-1019, 2011.

[6] K. A. Daltorio, S. Gorb, A. Peressadko, A. D. Horchler, R. E. Ritzmann, and R. D. Quinn, "A robot that climbs walls using micro-structured polymer feet," in *Int. Conf. Climbing Walk. Robots (CLAWAR)*, pp. 131-138, 2006.

[7] S. Kim, M. Spenko, S. Trujillo, B. Heyneman, D. Santos, and M. R. Cutkosky, "Smooth vertical surface climbing with directional adhesion," *IEEE Trans. Robot.*, vol. 24, no. 1, pp. 65-74, 2008.

[8] O. Unver, and M. Sitti, "A miniature ceiling walking robot with flat tacky elastomeric footpads," in *Proc. IEEE Int. Conf. Robot. Autom.*, pp. 2276-2281, 2009.

[9] M. W. Powelson, and S. L. Canfield, "Design of Track-Based Climbing Robots Using Dry Adhesives," in *Proc. ASME Int. Des. Eng. Tech. Conf. Comput. Inform. Eng. Conf. (IDETC/CIE)*, pp. V05BT08A020, 2017.

[10] H. K. Raut, A. Baji, H. H. Hariri, H. Parveen, G. S. Soh, H. Y. Low, and K. L. Wood, "Gecko-inspired Dry Adhesive Based on Micro-Nanoscale Hierarchical Arrays for Application in Climbing Devices," *ACS Appl. Mater. & Interfaces*, vol. 10, no. 1, pp. 1288-1296, 2018.

[11] T. Yanagida, R.E. Mohan, T. Pathmakumar, K. Elangovan, and M. Iwase, "Design and Implementation of a Shape Shifting RollingCrawlingWall-Climbing Robot," *Appl. Sci.*, vol. 7, no. 4, pp. 342, 2017.

[12] W. A. Breckwoldt, K. A. Daltorio, L. Heepe, A. D. Horchler, S. N. Gorb, and R. D. Quinn, "Walking inverted on ceilings with wheel-legs and micro-structured adhesives," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, pp. 3308-3313, 2015.

[13] M. P. Murphy, W. Tso, M. Tanzini, and M. Sitti, "Waalbot: An agile small-scale wall climbing robot utilizing pressure sensitive adhesives," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, pp. 3411-3416, 2006.

[14] AirStick Microsuction Tape by Sewell

[15] http://multimedia.3m.com/mws/media/1204168O/3m-vhb-tape-design-guide-high-res-pdf.pdf

[16] K. C. W. Liew, "Fabrication and characterization of biomimetic dry adhesives supported by foam backing material," Master's thesis, University of Waterloo, 2017.

[17] H. Shahsavan, and B. Zhao, "Bioinspired functionally graded adhesive materials: synergetic interplay of top viscouselastic layers with base micropillars," *Macromolecules*, vol. 47, no. 1, 353-364, 2013.

[18] V. D. Nguyen, G. S. Soh, S. Foong, and K. Wood, "Localization of a Miniature Spherical Rolling Robot Using IMU, Odometry and UWB," in *Proc. ASME Int. Des. Eng. Tech. Conf. Comput. Inform. Eng. Conf. (IDETC/CIE)*, in press, 2018.

[19] Q. He, M. Yu, Y. Li, X. Chen, H. Zhang, L. Gong, and Z. Dai, "Adhesion characteristics of a novel synthetic polydimethylsiloxane for bionic adhesive pads," *J. Bionic Eng.*, vol. 11, no. 3, pp. 371-377, 2014.

[20] M. P. Murphy, and M. Sitti, "Waalbot: An agile small-scale wall-climbing robot utilizing dry elastomer adhesives," *IEEE/ASME Trans. Mechatronics*, vol. 12, no. 3, pp. 330-338, 2007.