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Towards the Design of Gripper Independent of Substrate Surface Structures

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***Abstract*—**End effectors for robotic systems are becoming more and more advanced, resulting in a growing variety of gripping tasks. However, most grippers are application specific. This paper presents a gripper that interacts with an object's surface rather than being dependent on a defined shape or size. For this purpose, ingressive and astrictive features are combined to achieve the desired gripping capabilities. The developed prototype is tested on a variety of surfaces with different hardness and roughness properties. The results show that the gripping mechanism works on all of the tested surfaces. The influence of the material properties on the amount of the supported load is also studied and the efficiency is discussed.

***Keywords*—**Claw, dry adhesion, insects, material properties.

I. Introduction

PICKING up a variety of objects is an easy task for humans, but remains a challenge for robotic systems. Most grippers are designed for a defined task. The different mechanisms of gripping can be classified into four categories [1], namely (1) "impactive" - jaws or pinchers grasping the object by enclosing or clamping; (2) "ingressive" - hooks or needles penetrate the surface; (3) "contigutive" - chemical or thermal adhesion in direct contact with object; and (4) "astrictive" - electrostatic/magnetic forces or vacuum suction is applied on object.

Past research has focused on impactive systems imitating the grasping mechanism of human hands using two or more pinching fingers. A number of attempts have been made to develop a universal gripper [2]. A recent example is the universal gripper developed by Amend et al., which can grip all kinds of different shapes with the very simple and low-cost mechanism of jamming granular material, but it fails in picking up objects that are flat and bigger than the gripper [3], [4].

In addition to the shape grasping impactive grippers, astrictive grippers, particularly vacuum suction, are commonly used on flat surfaces, mainly in industry, because of the ability to continuously applying a holding force with precision and speed suitable for pick and place tasks [5]. One drawback of this mechanism is the limitation of the roughness and the shape of the surface interacting with the mechanism. Even though the mechanism can be altered to allow a certain extent of adjustment to the shape of the object [6], [7], close contact with the surface is still needed. Therefore, the surface is required to be smooth and its use is limited to materials like glass and metal.

Ingressive grippers on the other hand attach to an object by making use of its surface structures rather than adjusting to a form. NASA JPL developed a novel gripper that can lift and hold on to consolidated rock and rubble piles by using microspines [8]. Those were originally developed for the use on climbing robots, such as Spinybot, which could reliably climb a wide variety of rough surfaces with the micro-spines [9]. A similar mechanism, using claws, can also be observed in the RiSE robot [10].

Grasping objects independently on their shape is a challenge for universal grippers. For this purpose, astrictive and ingressive features are combined. This dual mechanism can be widely observed in insects like the dock beetle [11]. On rough surfaces, insects mainly use small claws located on the tips of their legs, specifically on the tarsi. It is shown to be sufficient if the surface roughness is lower or comparable in size to the diameter of the tarsal claws [12]. Insects are able to walk on smooth surfaces by the use of an attachment pad of dry or wet adhesion, which can support a considerably high load [13], [14]. Therefore, insect feet combine claws with adhesive pads which allow them to walk on rough and smooth surfaces of any angle.

In this paper, a simple system which combines the features of the ingressive and the features of the astrictive is presented. It uses dry adhesions inspired by geckos [15] as the astrictive and claws inspired by insects as the ingressive mechanisms. Combining the two mechanisms gives the ability to attach to surfaces with a wide roughness-range. A prototype of the designed gripper is manufactured and tested on different surfaces.

II. Material and Method

A. Design

The gripper is able to adhere to rough and smooth flat objects and be simple to use at the same time. Therefore, claws are combined with dry adhesion in a mechanism that requires no manual adjustment for the mechanism to choose the appropriate mechanism for each substrate. If the ingressive feature cannot adhere to the surface, then the adhesion should be used automatically.

The gripper is designed and modeled using CAD software, specifically SolidWorks 2013 (Dassault Systèmes SolidWorks Corp.). A system with three legs is chosen so it can adapt to different inclines in the surface when the claws are in use. An adhesive pad is located at the center of the system and is connected to three surrounding legs using cords to move the

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legs horizontally over the surface to be gripped, see Fig. 1. Each leg has claws on the underside and is fixed at the edges of the gripper by the use of rubber bands.

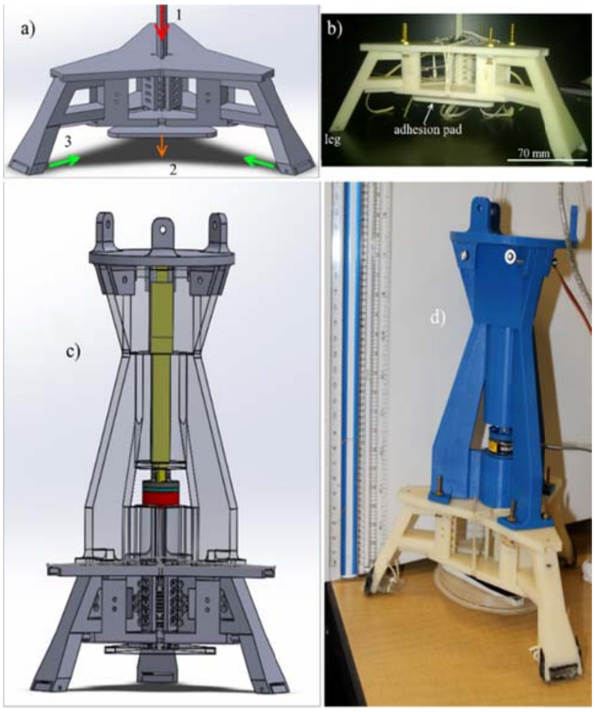

Fig. 1 (a) The designed CAD model of the gripper: The red arrow indicates the initialized movement of the motor (1) resulting in the orange arrows pushing down the adhesive pad (2) and sliding of the legs (3) (b) the fabricated gripper (c) an assembled CAD model of the gripper and the on top mounted embedment for the motor (yellow); the motor is attached to the compressive load cell (red), so the force can be measured, which is needed to push down the adhesive pad, (d) shows the fabricated gripper with the mounted motor and implemented load cell

The pad is designed to be in a higher position than the claws to protect it from unnecessary contact with the substrate if not in use. Pushing the adhesive pad downwards, in the direction of the orange arrow in Fig. 1 (a), pulls the cords. Which in turn move the legs, in the direction of the green arrows in Fig. 1 (a), towards the center, resulting in a stretching of the rubber bands. The movement of the legs causes the claws, attached at the tips, to scratch over the surface to attach. The claws lift up, when grabbing a smooth surface, allowing the pad to reach the surface and adhere to it. If that happens the legs are pushed upwards, so all of the preload force is applied on the adhesion. In order to detach the gripper, the adhesive pad is raised which results in the legs pushing the surface down, detaching it and the legs snap back to the starting position by the rubber bands.

The model of the gripper is shown in Fig. 1 (c). A linear actuator (L12 50-210-12-P, Firgelli) is used in order to push the adhesion pad downward, which in turn pulls the legs inward, highlighted in yellow color in Fig. 1 (c). The motor can provide a maximum power of 45 N. The fixation of the motor is also designed in CAD and fabricated using a 3D printer, see the blue part in Fig. 1 (d). The motor has an embedded position sensor which is used to measure the movement of the adhesive pad which is equivalent to the horizontal movement of the legs. A compression force load cell (LLB350, FUTEK) is used to measure the force applied to push down the adhesive pad and move the feet over the substrate, further referred to as the attachment force. For this purpose, the load cell was placed between the motor and the bar that pushes down the pad, shown in red color in Fig. 1 (c). The measurement of this sensor on rough surfaces is also indicates the amount of the shear force applied by the claws on the surfaces. For smooth surfaces, this force measurement indicates the preload force used to attach the adhesion pad to the substrate, because the claws are not in contact with the surface. The model is 3D-printed using thermoplastic ABSplus-P430 as the material and the assembly of the 3D printed gripper is shown in Fig. 1 (d).

A system of four claws is attached under each foot Fig. 2. Each claw is a bent fishing hook (R50-94840, size 16, Mustard) and mounted on a 5 mm wide strip of plastic, numbered 3 in Fig. 2. Connected by rubber bands, number 4 in Fig. 2, the four claws were aligned and fixed as shown in Fig. 2. This gives some compliancy of horizontal and vertical flexibility in order to enable the individual movement of each claw to adapt to the surfaces. The complete gripper including sensors, the actuator and its mounting had a weight of 556.56 g. Controlling the actuator and the acquisition of data from the load cell is achieved using LabVIEW 2013 (National Instruments).

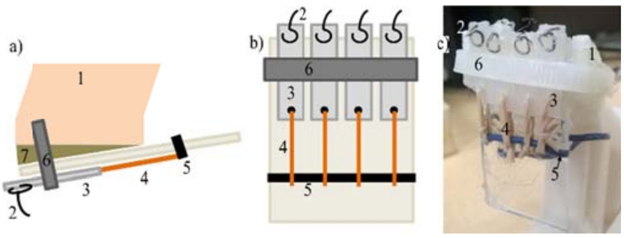

Fig. 2 Sketched (a) side view and (b) front view of the claws system on the underside of each leg to allow an individual movement of each claw, (c) shows a realized prototype: 1 leg, 2 claw, 3 plastic strip to mount the claws on, 4 rubber band, 5 wire to align claws, 6 plastic strap to keep the claws in plane, 7 spacer to hold appropriate inclination angle

B. Testing Surfaces

Various materials are used to test the novel gripper's ability to grasp. The tested materials differ in roughness and hardness and could be divided into three categories: (1) Soft substrate, claws are able to penetrate the surface; (2) Rough and hard substrate, claws stick to the surface by catching on structures on the surface or slightly penetrate the surface; and (3) Smooth and hard substrate, which do not interact with the claws. The conventional Styrofoam, material 1, and cork, material 2, are selected as the soft materials. Wood, material 3, and synthetic rubber with a strengthening grid, material 4, are harder than materials 1 and 2 but also have a certain roughness, so the hooks are able to slightly penetrate the surface and hook into minor surface irregularities. Also, sandpaper, material 5, and porous conglomerate rock, material 6, are tested to investigate the ability to catch on to surfaces with major surface irregularities. The tested smooth surfaces, materials 7 to 9, which are Plexiglas, aluminum and lacquered wood, vary marginally in their surface roughness.

The hardness and roughness of the materials are tested to identify the properties of the materials. The hardness of the materials is examined with the hardness tester REED HAT-6510A (FUTEK) while the roughness is examined by using a portable Surface Roughness Tester Surftest SJ-400 (Mitutoyo). Only the shore test is used to measure the hardness of the soft materials. The hardness of the hard materials, i.e. materials 5, 6, 7 and 8, are not measured, because the claws are not able to dig/cling into hard surfaces, rather it depends only on the irregularities of the surfaces. The roughness and the hardness for the different materials are measured and listed in Table I.

C. Experiment

A flat piece of each material is used to test the gripper's performance. Five test cycles are used to perform the test on the nine substrates. One test cycle represents testing of all surfaces once. New claws are used for each test cycle to guarantee their sharpness.

The gripper is positioned on the testing surface, which is clamped to the ground. A load of 1.1 kg on the top of the gripper is used to apply a pre-defined load on the tested surfaces. The motor is then initialized to pull the legs inward to cling to the rough surface. The legs' movement is stopped once the force required to pull the legs exceeds the motor's maximal force. The legs stop moving because they either cling to the surface or reach the end of their range of motion.

A tension and compression load cell (LCM300, FUTEK) is attached to the shaft holding the adhesive pad to measure the detachment force, which represents the maximum load the gripper is able to lift. The acquisition of data from this load cell is also achieved using LabVIEW 2013 (National Instruments).

If the legs do not cling to the surface, i.e. the surface is smooth, then the legs are moved inward until the adhesion plate's level becomes lower than the claws and the adhesion is automatically applied to the surface. The gripper is then pulled up until it detaches from the surface. Over the course of testing, the occurring responses of the two force sensors and the motor positions over time are measured.

The load force measurements are analyzed statistically using one-way ANOVAs and are used to determine the difference in the considered characteristics. The force needed to attach to the surface, the maximum load and the leg movement of the five tests (n = 5) are analyzed for the tested materials. The materials are separated into two groups, materials 1-6 as group 1 and materials 7-9 as group 2, and each group is analyzed separately. Furthermore, the influence of hardness and roughness, on the maximum load the gripper could lift is also examined via multiple regression for the first four materials.

It is observed that the hard surfaces of the plexiglass, aluminum and the lacquered wood showed scratch marks formed by the claws. Concerning the rough surfaces, as mentioned, only the soft substrates of Styrofoam and cork showed some damage on their surface structures, while on all other surfaces hardly any scratch marks could be seen on them. In addition to the successful attachment to the different tested materials, the gripper is also successful in detaching from all materials.

TABLE I
THE DIFFERENT TESTED MATERIALS WITH THEIR CHARACTERISTICS AND THE MAXIMUM SUPPORTED LOAD

Material	Hardness	R_a $[\mu m]$	R_z $[\mu m]$	Max. load [N]
1 Styrofoam	23.34	7.77	45	3.59 ($\pm$1.82)
2 Cork	55.4	17.15	4.98	4.98 ($\pm$2.43)
3 Wood	91	7.44	5.46	5.46 ($\pm$3.14)
4 Rubber	83.32	9.33	5.82	5.82 ($\pm$0.98)
5 Sandpaper	–	111.87	1.69	1.69 ($\pm$1.1)
6 Stone	–	36	2.29	2.29 ($\pm$2.56)
7 Plexiglass	–	0.06	17.36	17.36 ($\pm$3.76)
8 Aluminium	–	0.21	5.64	5.64 ($\pm$3.71)
9 Lac. wood	–	5.17	2.14	2.14 ($\pm$1.32)

Listed are the test surfaces, identifiable by their material and an associated number from 1-9. Materials 1-6 represent rough surfaces and 7-9 are considered smooth substrates. The hardness was measured in Shore A and the surface roughness was determined by Ra, which is the arithmetic mean of the absolute values of the peaks and valleys and Rz, the ten-point averaged overall height of the irregularities in μm. Descriptive statistics of all tested materials is in the last column of the table, giving the averaged values and its standard deviation (m ± sd) for n = 5 for the maximum supported load.

III. RESULTS

The process of each gripping test is divided into five steps. Fig. 3 shows the steps for one of the tests performed on the wood as an example. In the first step in Fig. 3, the legs of the gripper are kept at their initial position. During step 2, in Fig. 3, the motor is activated to push the adhesion pad downward; consequently, the legs are moved horizontally over the tested surface. The increase in the compressive load cell force reading is due to the friction between the claws and the surface and the counteracting force of the rubber bands on the legs. The motor is turned off in step 3, which shows a small decrease in the force due to a backlash in the motor.

Step 4 shows the forces behavior for the gripper while it is pulled up until it detaches from the surface. The force peak, which represents the force right before the claws detach from the surface, is the maximum force the gripper can hold. The force measured by the compressive load cell is decreased simultaneously because the forces counteracting the claws' movement are removed. Finally, the gripper is detached from the surface, see step 5 in Fig. 3. The compressive force did not return to its zero value because, the rubber bands are still pulling the legs to their original position. The maximum load value is detected by taking the highest value of the data and the maximum attachment force is determined by averaging four points of the force plateau seen in the compression force measurements in Fig. 3. The mean values (n = 5) of all tested characteristics are shown in Table I and the results of the ANOVAs are listed in Table II.

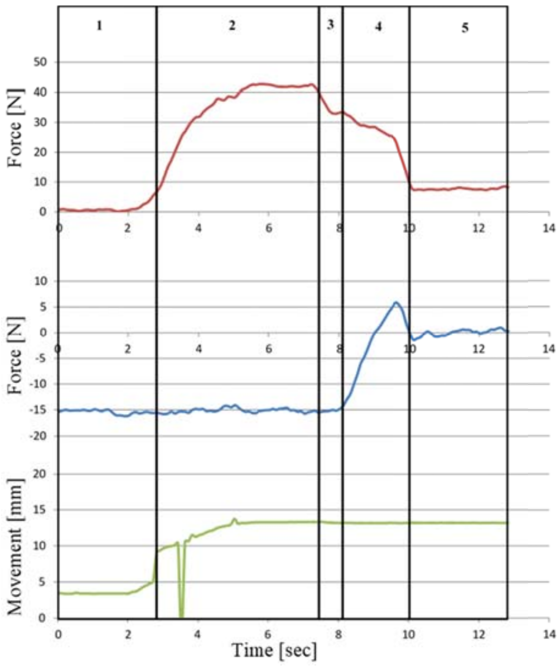

Fig. 3 Signals picked up during a test on the wood. Shear force (red), max load (blue) and position of the legs (green) are shown over time. The signals of the load cells have been converted to N and the distance travelled is shown in mm. The process can be divided into 5 steps: 1 lowering the gripper (to get in contact with the wood surface), 2 lowering the adhesive pad, 3 stopping the motor, 4 pulling up the gripper to detach and 5 when the end position is reached

The detachment forces measured on the rough surfaces are in a range between 1 N to 10 N, depending on the surface. Fig. 4 shows that the layered wood and synthetic rubber could support the highest loads amongst the rough materials, followed by the soft materials of cork and Styrofoam, while only a very small load is supported for the stone and the sandpaper. However, the high standard deviations throughout the tests suggest that the efficiency varied between the tests. The reasons of gripper detachment differ between the materials. Materials 1 and 2 could not withstand the pulling force. Because of their softness, the claws are able to grip into the surface, but the materials broke up and could not support the hooks, resulting in the detachment of the hooks.

Lifting materials 3 and 4 seemed to be more effective, because the claws did penetrate the substrate, but since the materials are stronger, they were able to withstand the rupture of the substrate. However, since the surface structures are only minor, the hooks slipped off with the increase in loads. The reason of failure while gripping to materials 3 and 4 is the hooks' slippage at higher loads. Even though materials 5 and 6 have high roughness, the gripper is hardly able to pick them up. The friction on those surfaces lead to high shear forces causing the hooks to get stuck quite easily, but the claws could not hold on to the irregularities after lifting which result in the detachment of the gripper. The adhesion was able to pick all of the smooth surfaced materials. The lower the roughness, the higher the supported load.

TABLE II
ANOVA Test for the Different Materials

	Rough surfaces (1 - 6)				Smooth surfaces (7 - 9)			
	df	error df	F	p	df	error df	F	p
Attachment force	5	24	2.22	0.086	2	12	23.47	0.000
Max. load	5	24	5.56	0.002	2	12	46.35	0.000

Inferential statistics of the ANOVAs for the characteristics attachment force, maximum load and leg movement between the different materials with df showing the degrees of freedom.

ANOVA shows a significant difference amongst the rough surfaces, which indicates that the efficiency of the gripper to lift a plane is dependent on the roughness of the surface ($F(5, 24) = 5.56$, $p = .002$). Similarly, a significant difference could be seen between the maximal supported load of smooth structures ($F(2, 12) = 46.36$; $p < .001$). The more irregularities the surface had, the smaller the load it could lift. Because of the high roughness, not all of the hooks are able to hold to the surface.

The analysis of the multiple regression for the rough materials, materials 1 to 4, which are picked up by using the claws, showed a significant correlation. Materials 5 to 8 are not included in the regression, as their hardness is not measured. The regression coefficients show a negative influence of the roughness (-0.0369) and a positive one of hardness (0.0321) on the maximum load.

The resulting regression functions for the materials that are lifted through the use of claws could be given by the following equation:

$$y = 2.4956 + 0.0321 \cdot x_{hard} - 0.0369 \cdot x_{rough} \tag{1}$$

where, y is the predicted maximum load in Newton, x_{hard} is the value of the Shore hardness and x_{rough} is the value for the roughness in mm. The error between the regression model and the real experiment values has a maximum error of 5%.

IV. Discussion

As seen in the results, the proposed gripper is able to lift all surfaces, even though only a small load is supported for the materials with high roughness. The great advantage lies in the simplicity of the system. No sensors are needed to choose a suitable attachment method for the surface to be gripped and only a simple up and down motion is required. Therefore, the gripper is easy to control. A self-stop mechanism can be implemented, if the system is programmed so that the motor stops its movement if a certain force is exceeded.

The gripper is able to grip to the rough surfaces, both hard and soft, as the claws either partially penetrate the surface or grip to the irregularities in the surface. The gripper also utilizes the adhesion pad to pick up the hard smooth surfaces.

The gripper's adhesion is efficient for very smooth surfaces (Fig. 4). The greater the roughness of the surface is, see Table I, the less the load the gripper can support when the adhesion is used. The used single layer adhesion pad is made up of very small posts shaped like mushroom of PDMS. Which upon contact with other materials form intermolecular interactions with the surface in contact [16], [17]. The bigger the contact area is, the more intermolecular interactions there are, leading to stronger adhesion force. Rougher surfaces result in small contact area because of the irregularities on the surface and consequently weaker contact force. Using adhesions with hierarchical structure, which can adapt better to uneven surfaces, should increase the lifting force and help grasping rougher surfaces than the dry adhesion pads do [18].

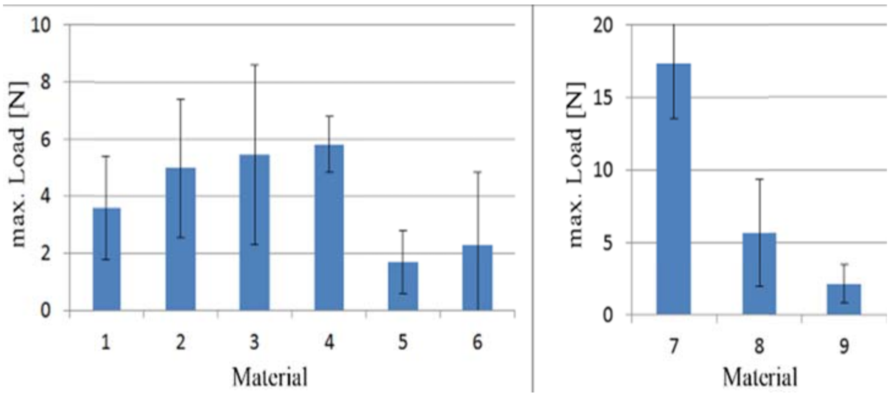

Fig. 4 Graphical comparison of the averaged (n = 5) force measurement converted into Newton, of the max that could be supported by each material. The standard deviation1is indicated in error bars. 1 Styrofoam, 2 cork, 3 wood, 4 rubber, 5 sandpaper, 6 stone, 7 Plexiglas, 8 aluminum, 9 lacquered wood

Very rough surfaces are harder to grip because it is hard to engage all of the hooks on those surfaces. By looking to Table I, the supported load for the rough materials 3 to 6 which picked up without the claws penetrating the surface, depends on R_z. If a high number of hooks are guaranteed to interlock to the surface, then the gripper would easily support high loads [8]. In fact, NASA JPL showed that only 10 % to 30 % of the hooks, on their gripper, are actually able to grip to the surface. Using more claws will increase the efficiency of the gripper to pick rough surfaces. This is also supported by the high standard deviation Fig. 4. If enough claws did interlock in appropriate irregularities then a much higher load could be supported than in other tests on this material, which explains the variation in the maximum load between the different testing cycles. Therefore, a much higher number of hooks should be used.

Even though the detachment process caused little damage on the soft surfaces, like Styrofoam and cork, the marks can be considered minor due to the small dimensions of the hooks. On all other rough materials no damage could be seen. The minor scratches on smooth surfaces could be avoided if the preload is applied after the claws are lifted. In order to do this the gripper could be equipped with a sensory system that detects the roughness of the surface and the picking mechanism is altered accordingly.

Even though the introduced gripper is a primitive system, it proves that the newly designed mechanism works and can be enhanced by adding sensors and optimizing the design. The future goal for a novel universal gripper should have the ability to pick up planar objects by adhering to the structure of the substrate. This could later on be transferred to an impactive system, resulting in a very complex gripper capable of interacting with a wide variety of objects with different surfaces and shapes.

V. Conclusion

The novel gripper is able to attach to all of the tested surfaces and therefore the hybrid mechanism is a promising approach towards the development of a universal gripper. Such a gripper could be useful in applications that require dealing with objects of different material properties.

One application could therefore be in construction sites, where stone and wood as well as window glasses are needed to be handled. Another possible application might be in the field of climbing robots. An abstracted form of the mechanism could be implemented at the tips of the legs and use it as feet. This would enable the robot to overcome a wide variety of surfaces without requiring further changes in its design.

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