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Granular jamming based robotic gripper for heavy objects

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Abstract. Moving heavy objects with overhead cranes requires the operator to fasten the object to a hook with ropes or chains. This is a time-consuming process, which could be avoided by using universal grippers that can lift objects of any shape. This study was conducted to find if a universal gripper, based on granular jamming, can be used for crane scale applications. Maximum lifting capacity of granular jamming grippers was analytically evaluated and experimentally tested with various material combinations. Objects with different shapes, sizes and weights were successfully lifted with selected gripper configurations. The results showed that grain size and grain compressibility both affect the performance of the gripper. It was demonstrated that in order to efficiently lift heavy objects with granular jamming, the granular material has to be compressed sufficiently. Pressure difference between environment and the sealed pouch, filled with granular material, has to be correct. With this setup, gripper based on granular jamming was able to lift objects with various shapes; and weights up to 120 kg.

Key words: granular jamming, crane, lifting, universal gripping.

1. INTRODUCTION

The technology for lifting heavy objects has always relied on strong hooks and some manual labour for attaching an object to the hook in various ways. Usually, in case of lifting objects with the overhead crane, the objects are attached to the hook with chains or ropes. This system, having two mass nodes attached to ropes, is slow and prone to double pendulum dynamics [1]. Also, this system requires workers to work constantly in dangerous environment around the hook. Usually a person has to attach objects manually. Removing the attachment step could save a lot of time and increase safety of the work environment.

Gripping technology in robotics has recently taken big steps towards universal gripping. Universal grippers can lift objects with variable shapes [2]. Current gripping technologies can be divided into three different categories, enabling grasping by: (1) actuation; (2) controlled stiffness; and (3) controlled adhesion. Actuation covers all traditional gripping technologies, such as different rigid jaw grippers and stiff grippers driven by complex algorithms. It also covers the compliant materials deformed during gripping process [3]. The problem with gripping by actuation is that it can be rather clumsy with various shapes and can even cause harm with applied forces [4].

Adhesion-based grippers are able to grip objects with a shear force that is applied on the lifted object. This kind of lifting method can be used to lift large, deformable and easily breakable objects. One way of making an effective adhesive gripper is to put very thin and adhesive micro-sized planes or hairs on the gripping surface of the gripper. When the gripping surface has been placed on the object and applied with shear force, the contact area between the object and the bending micro planes grows. For example, in the nature gecko uses this method when walking on vertical walls. This technique can be used to lift objects in the range of few kilograms, without squeezing them [4].

The idea behind gripping by controlled stiffness is setting the gripper's structure in its soft configuration for enveloping the target object to be grasped [3]. The

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gripper is then stiffened so that it grips the target object. One example of this is granular jamming where a sealed and airtight pouch is filled with granular material. When the pouch is at its soft configuration, it can be deformed easily and its contents has fluid-like behaviour in macro-scale. After sucking out the air from the pouch, the granules get jammed and the pouch stiffens to its deformed shape around the target object [5]. The granular jamming process can even be sped up by adding positive pressure during deformation and releasing stages of the gripping process [6]. Stiffness can also be controlled by alloys that change their phase from solid to liquid, depending on the temperature. There are also some fluids that respond to electric and magnetic fields by changing their viscosity [3].

Developments in industrial robotics have gained promising results using granular jamming for lifting objects [3]. For example, Empire Robotics has successfully lifted objects with the mass of around 10 kg with a 16.5-cm-diameter-gripper [7]. Thus, this technology might be viable option for substituting some of the crane lifting that use ropes; and for lifting objects weighing less than few hundreds of kilograms. However, the maximum capacity for such kind of lifting method is still unknown. This study documents the scalability of the gripper based on granular jamming by scaling the size of the pouch and testing different granular materials.

2. MODEL FOR LIFTING CYLINDRICAL SHAPES

The gripper consists of a large pouch filled with granular material, a body to support the pouch, and a vacuum pump. The gripper assembly is lifted on top of a cylindrical object with radius r and height d (Fig. 1a). The lifting capacity of a gripper based on the granular jamming is hard to estimate as it depends on the shape of the object. Below, the maximum lifting capacity for lifting a cylindrical-shaped object is estimated analytically.

When air has been evacuated from the pouch, the change of the radius is δR. This results in decrease of the radius of the pouch's horizontal cross-section, δr (Fig. 1b). It is assumed that the radius of a cylinder does not change, i.e. the lifted object has a stiffness much larger than that of the granular material. The normal force that hinders contraction can be calculated from the following relationship:

$$\delta r = 0 \Rightarrow \varepsilon_{rr} = 0, \tag{1}$$

and using Hooke's law we get

$$F_N = \frac{\delta r}{r} A_0 E. \tag{2}$$

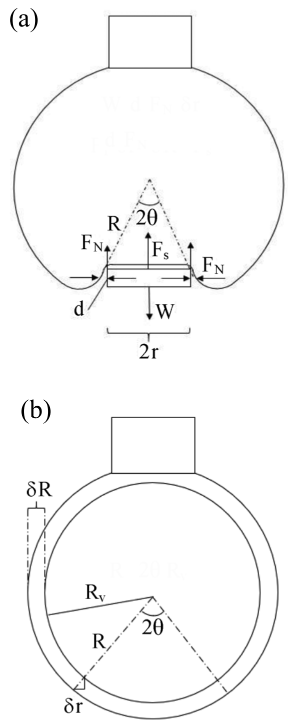

Fig. 1. (a) Free body diagram of the gripper lifting a cylinder; (b) Volume change of the gripper moves each point of the pouch in horizontal direction, change of the radius is δr. The large circle represents the cross-sectional side view of the gripper in its initial configuration and the smaller circle represents the gripper when the air has been evacuated.

Slipping occurs when the pressure inside the low-pressure pocket between the top face of the cylinder and the membrane is higher than gripping pressure at the walls of the cylinder. The following relationship holds

$$P_v = \frac{F_N}{A_0}. \tag{3}$$

The suction force caused by the low-pressure pocket is

$$F_s = P_v A_c, \tag{4}$$

where A_c is the area of the top of the cylinder. Now putting these together gives

$$F_s = F_N \frac{A_c}{A_0} = F_N \frac{r}{2d}. \tag{5}$$

The change in the cross-sectional radius is

$$\delta r = \delta R \sin(\theta). \tag{6}$$

Since the angle θ depends on the height of the cylinder inside the gripper, the total force can be found by summing all the differential force elements along the height of the cylinder. The maximum lifting weight of the gripper is then

$$W_{max} = F_s + F_N,$$

$$W_{max} = 2\pi\mu E\delta R\int_0^d \frac{r}{\sqrt{(R-h)^2 + r^2}}\,dh\left(1+\frac{r}{2d}\right), \quad (7)$$

where E is the Young's modulus of the granular material, R is the radius of the gripper, r is the radius of the cylindrical object, d is the height of the cylindrical object, h is the height of the cylindrical object, μ is the coefficient of static friction, and δR is the change of the gripper's radius.

The change in radius of the gripper can be written in terms of the volumetric strain:

$$W_{max} = 2\pi\mu ER\left(1-\sqrt[3]{1-\frac{\delta V}{V}}\right) \times\left(\tan^{-1}\left(\frac{R-d}{r}\right)\right)\left(\frac{1}{r}+\frac{1}{2d}\right). \quad (8)$$

It can be seen that variables, which can be affected by design of the gripper, are: *radius of the gripper*, *volumetric strain* and the *Young's modulus* of the granular material. The volumetric strain is proportional to the pressure difference between the inside and outside of the gripper membrane (bulk modulus). Therefore, a sufficiently powerful vacuum pump is essential for the gripper to provide high gripping forces. The choice of granular material is also essential for the gripper to provide high gripping forces. Young's modulus of the granular material must be high enough to be able to compress and deform around various objects.

It should also be noted that the gripping strength depends on the geometry of the gripping object, not only on the contact surface area but also on the contact angle. The contact angle was assumed to be 90 degrees in these calculations, i.e. the object's contact surface is perpendicular to the ground.

Figure 2 illustrates the maximum lifting capacity for the cylinder with radius of 15 cm and height of 10 cm as

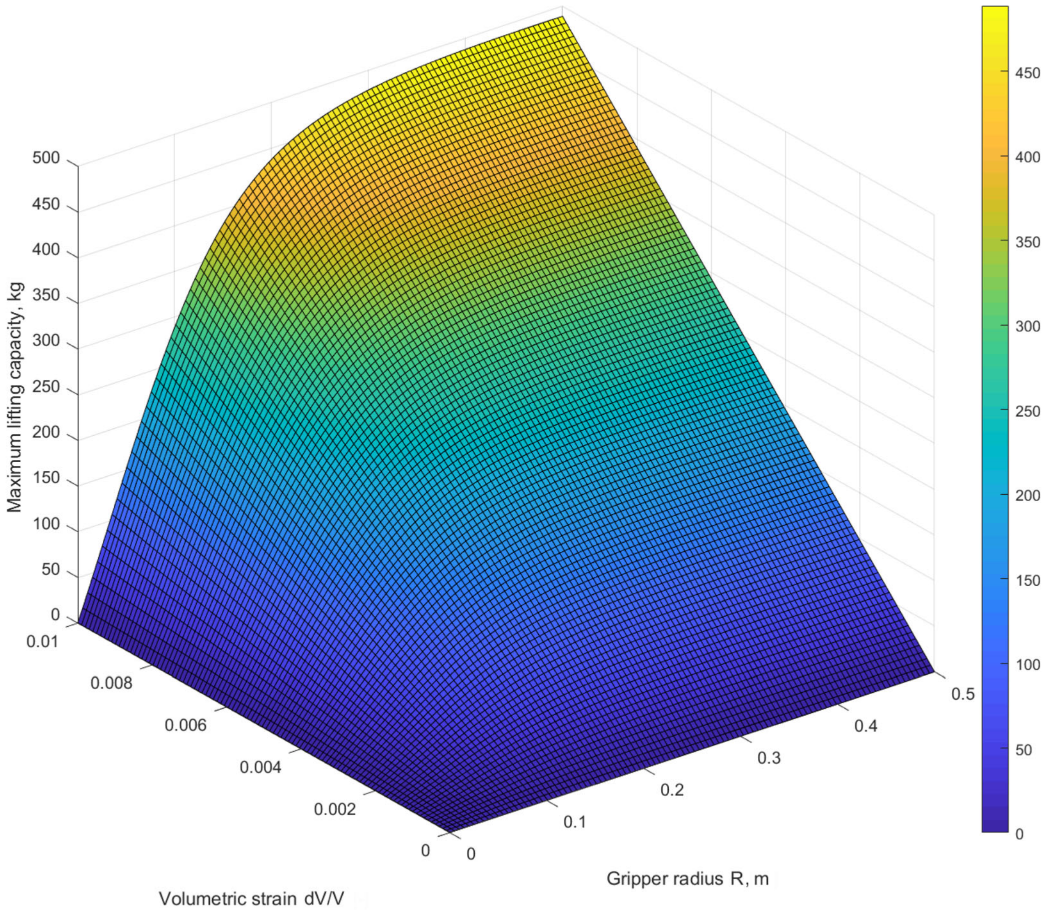

Fig. 2. Design variables vs maximum lifting capacity for a cylinder with r = 0.15 m and d = 0.1 m. The volumetric strain was assumed to be dV/V = 0.004 and the radius of the gripper R = 0.325 m. Value of the volumetric strain was taken from previous research [5]. Plot was produced with MatLab.

a function of volumetric strain and radius of the gripper. Granular material used in the calculation is coffee and the values for the stiffness, friction coefficient and volumetric strain were taken from previous research [5].

3. EXPERIMENTAL DESIGN

In order to gain some knowledge about the effect of granules' size on the gripping force, wooden pellets were chosen as the first test material (Table 1). The same wooden pellets in a ground form were chosen to be the second material, to achieve smaller particle size. The wooden pellets were chosen for their relatively advantageous stiffness-lightness ratio. The third granular material used for the study was plastic granules, which were even lighter and stiffer than wooden pellets. The fourth test material was sand, which has very high stiffness and very high density. Fifth material was rubber granules for their elasticity. The rubber granules were similar to the ones used in artificial football fields. All granules are shown in Fig. 3.

A typical exercise ball was chosen to be the surface material of the gripper (Table 2). The sheer weight of the granular material inside the gripper's pouch can cause great stresses to the surface material and break it. Thus, a custom pouch was made of carbon and glass fibre composite. The composite pouch was then sealed with silicone coating.

The rest of the system includes a custom rigid structure connecting the pouch with the hook of the crane. Also, a suction system was connected to the rigid body in order to create pressure difference between the contents of the membrane and environment. The vacuum machine used was Robinair single stage vacuum pump achieving an ultimate pressure of 0.2 bar. The pump and outlet valve in the frame body were controlled by the smartphone application via Bluetooth with an Arduino UNO, a relay and a servo motor. The final setup can be seen in Fig. 4.

4. TESTING ENVIRONMENT

Testing was done with multiple different combinations of granules and membrane surface materials. The combinations are listed in Table 3. Every combination of the test material was put through the same sequence of lifting tasks.

Lifting tasks were performed by placing the lifted object on the ground and lowering the gripper on top of the object. The gripper was lowered until it was no longer hanging from the crane but rather resting on top of the test object. The absolute pressure inside the gripper was lowered to approximately 0.6 bars using the 0.19 kW vacuum pump.

The first task was to lift a 1 kg plastic bucket (Table 4) to make sure the vacuum pump was working

Table 1. Granular material parameters

Granule material	Granule size, mm	Density, kg/m^3	Stiffness, GPa
Wooden pellets	d = 6+/–0.2; l = 15.6+/–5	696	1
Ground wooden pellets	d = 6+/–0.2; l = 5 +/– 2.5	469	1
Plastic granules	2.5	602	3
Sand	0.5–1.5	1559	50
Rubber granules	2.5	535	0.1

Fig. 3. Five different types of granular materials starting from the left: plastic granules, ground wooden pellets, rubber granules, fine sand; and wooden pellets.

Table 2. Pouch surface material parameters

Reference	Materials	Tensile strength	Elasticity	Thickness, mm	Diameter, cm
Exercise ball 1	PVC	Low	High	1.5	65
Exercise ball 2	PVC	Low	High	1.5	85
Custom ball	Silicon coating, carbon fibre/glass fibre layer	High	Low	2–4	65

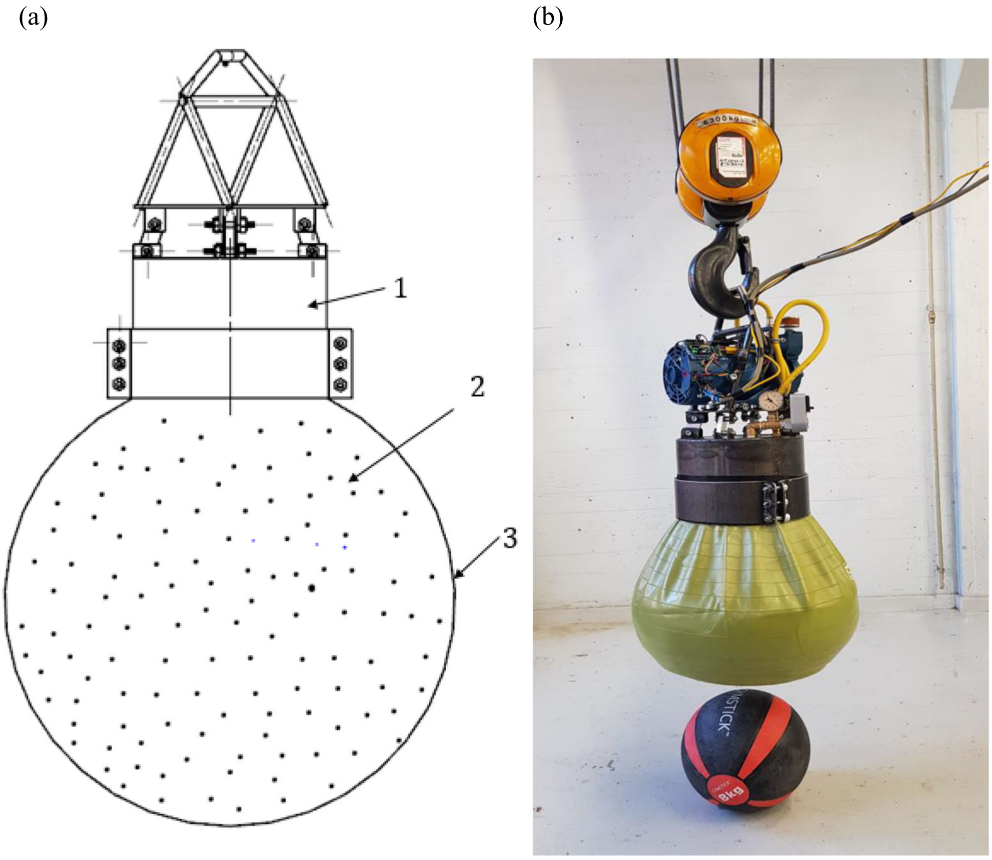

Fig. 4. (a) Gripper configuration consisting of the following components: the frame body (1); granular material (2); and the gripper's surface material (3). (b) Final gripper assembly with vacuum pump mounted on top.

Table 3. Combinations of tested materials' parameters

Combination	Granular material	Pouch surface
1	Wooden pellets	Exercise ball 1
2	Ground wooden pellets	Exercise ball 1
3	Plastic granules	Exercise ball 1
5	Sand	Exercise ball 1
6	Wooden pellets	Exercise ball 2
7	Wooden pellets	Custom ball
8	Rubber granules	Exercise ball 1

properly. The following three tasks included lifting three various objects weighing roughly 5–10 kg, to evaluate the grip on complicated shapes. These three different objects were: a stool, a fire extinguisher and a gym ball. The next task was to lift a trash bin with sand and metal filling, weighing 30 kg. The final object was a 120 kg steel cylinder with a hook attachment protruding from the top. Test objects, except for the 1 kg plastic bucket, are displayed in Figs 5a–5e. Lifting tasks were classified either as a success or a failure.

A task was successful if the gripper could lift the object and hold it up for 30 seconds. Lifting task could be repeated up to ten times before it was classified as a failure. Ten trials were given since finding out the optimal grip requires multiple trials. One successful lift was enough to classify the test successful.

Table 4. Test objects and dimensions

Test object No.	Object	Radius, cm	Height, cm	Weight, kg
1	Plastic bucket, standing	10	30	1
2	Stool, standing	32	57 (2.5 cm contact area)	5
3	Gym ball	28	–	8
4	Fire extinguisher, laying	15	42	9
5	Trash bin filled with sand and metal weight, standing	27	30	30
6	Steel cylinder, standing	25	35	120

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

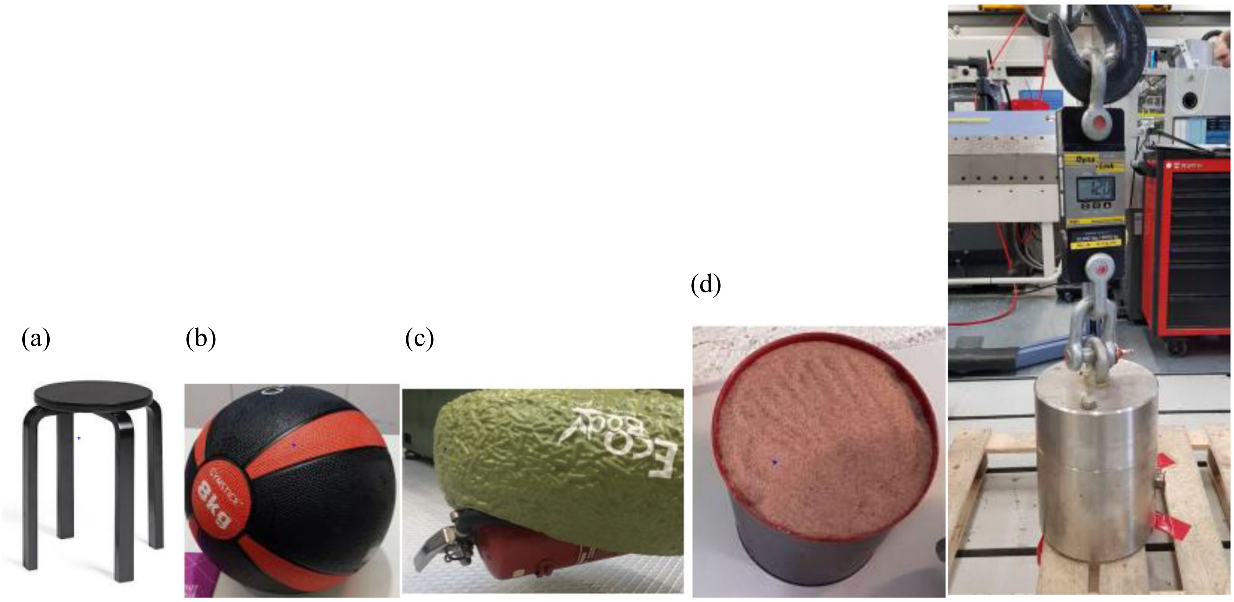

Fig. 5. Test objects: (a) a stool (picture does not present the actual test object); (b) gym ball; (c) fire extinguisher; (d) trash bin filled with sand; and (e) steel cylinder. Plastic bucket is not shown in the figure.

5. RESULTS

Tests of the granular materials and membrane materials were performed according to the previous section. The results of the tests are listed in Table 5.

In general, only 0.2 bar pressure difference was usually enough to generate sufficiently tight gripping for lifting. 120 kg cylinder required more than 0.5 bar pressure difference for successful lifting. The heavier the object, the higher was required pressure difference between environment and the pouch.

The tests made with smaller exercise ball and wooden pellets showed promising results. This combination was able to complete first five tasks. However, tests to lift

Table 5. Test results for each combination of granular material and surface material of the gripper

No. of test object and the combination	1	2	3	4	5	6
1 Exercise ball 1, wooden pellets	Success	Success	Success	Success	Success	–
2 Exercise ball 1, ground wooden pellets	Success	Success	Success	Success	Success	Success
3 Exercise ball 1, plastic granules	Success	Success	Success	Success	Success	Failure
4 Exercise ball 1, sand	Success	Success	Failure	Failure	Failure	Failure
5 Exercise ball 2, wooden pellets	Failure	Success	Failure	Failure	Failure	Failure
6 Custom ball, wooden pellets	Failure	Success	Failure	Failure	Failure	Failure
7 Exercise ball 1, rubber granules	Success	Success	Success	Success	Success	Success

the 120 kg cylinder were not carried through as it took multiple trials to lift successfully objects 3, 4, and 5. The second test was done with the smaller exercise ball and the ground wooden pellets. This combination gave better results than the first one, and completing the task of lifting the first five tasks was successful already with the first trial. The gripper was also able to lift the 120 kg steel cylinder during ten trials.

Plastic granules performed well, lifting successfully the first five tasks within given ten trials. However, this combination was not able to lift the 120 kg cylinder. Sand showed poor results, completing successfully only first two tasks. The larger exercise ball and the custom ball showed poor performance being capable of lifting only the 5 kg stool.

The best combination seemed to be smaller exercise ball filled with rubber granules. All lifting tasks were marked successful with this combination already with the first trial.

Fig. 6. Large wrinkles forming on the gripper's surface, when the gripper with ground wooden pellets as granular material was evacuated of air.

6. DISCUSSION

Granular materials with higher compressibility gave the best results. As mentioned, the maximum lifting capacity depends on the volumetric strain of the gripper. The volumetric strain increases if the volume of the granular material can be compressed. This results in higher gripping forces and thus a larger lifting capacity. If the material is compressible it also deforms more easily around the surface of the lifted object. This in turn results in a larger contact surface area between the object and the gripper and therefore also larger gripping forces.

The most compressible granular materials were the ground wooden pellets and the rubber granules. This was indicated by the large wrinkles formed on top of the gripper's surface after evacuation of the air (Fig. 6). These materials gave also the best test results, supporting analytical model. It should be noted that sand was the poorest granular material, and it was also the least compressible material.

Comparing test results with the analytical solution it has to be kept in mind that granules were assumed to be similar to the ground coffee. The material, which resembles coffee the most is the ground wooden pellets. This material has similar size of granules and it is compressible. Equation (8) gives a maximum lifting capacity of approximately 270 kg for objects that have similar shape with the test object 2. This is above the weight of the heaviest test object.

Considering combination 2, it is most likely that the maximum lifting capacity for objects with similar shape as object 6 is somewhere near 120 kg. Object 6 was successfully lifted only once with this combination. However, combination 7 successfully completed the same task with the first trial. This might be due to higher compressibility of the granular material. The maximum lifting capacity of combination 7 can be relatively near to the analytical approximation of 270 kg. However, finding the maximum lifting capacity for combination 7 requires further experiments.

According to Eq. (8), the gripper's lifting capacity is proportional to the radius of the gripper. Larger radius should give a larger lifting capacity. The tests showed that the larger exercise ball gave poor performance quality, as it was only capable of lifting the stool. It must be noted that only 50% of the larger exercise ball was filled up with granules while performing the tests. Other balls were filled up to around 80%, which is enough to leave enough space for free movement between the granules before jamming. Further testing with gripper radii should be done to verify the relationship in Eq. (8).

Among the same type of granular materials, the one with the smallest granule size performs the best. This can be seen when comparing tests with wooden pellets and ground wooden pellets. It took multiple trials to successfully lift the first five objects with combination 1, and only one trial per object with the combination 2.

Previous studies [5] have shown that it is possible to use granular jamming to lift objects with various shapes. Current study showed that it is possible to use granular jamming in crane-scale applications. This kind of universal gripper based on the granular jamming would be suitable for lifting objects with various shapes and sizes, weighing up to 120 kg. Such a gripper could be used in machine shops or warehouses where heavy objects with irregular shapes are moved frequently.

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Teratihil põhinev haarats raskete esemete teisaldamiseks

Jesse Miettinen, Patrick Frilund, Iiro Vuorinen, Petri Kuosmanen ja Panu Kiviluoma

Kraanadega raskete esemete teisaldamiseks peab operaator kinnitama teisaldatava eseme köite või kettide abil kraanakonksu külge. See on aeganõudev protsess, mida saaks vältida universaalsete haaratsite abil, mis võimaldavad tõsta mistahes kujuga esemeid. Uuring viidi läbi selleks, et teada saada, kas graanulite teratihil põhinevat universaalhaaratsit saab kraanade jaoks kohandada. Graanulite teratihil põhineva haaratsi maksimaalset tõstevõimet hinnati analüütiliselt ja katsetati erinevate materjalide kombinatsioonidega. Erineva kuju, suuruse ja raskusega esemed tõsteti valitud haaratsikonfiguratsioonide abil edukalt üles. Tulemused näitasid, et nii graanuli suurus kui ka selle kokkusurutavus mõjutavad haaratsi jõudlust. Tõestati, et teratihtimise abil raskete esemete tõhusaks tõstmiseks peab graanulimaterjal keskkonna ja graanulimaterjali kinnise tasku tekitatud rõhkude erinevusest tingitult olema piisavalt kokku surutud. Katseseadistuses suutis teratihil põhinev haarats tõsta erineva kuju ja massiga kuni 120 kg raskusi esemeid.