A method to control grip force and slippage for robotic object grasping and manipulation

Pavel Dzitac, and Abdul Md Mazid, *Member, IEEE*

Abstract— **A grip force and slippage control for robotic object manipulation, based on mechanical friction is presented. This approach allows a load to be held reliably in the robot gripper without application of excessive forces or allowing uncontrolled slippage. It is a simple, robust and low cost solution, and could be used for applications where low cost integrated grip force and slippage control are needed. This solution could be customized to provide reliable grip force and slippage control for light, medium or heavy load holding applications for a variety of different objects.**

Keywords – slippage, grasp

I. INTRODUCTION

THE development of object slippage control for robotic grasping and manipulation has so far proven to be a significant challenge for researchers because it is difficult to determine reliably (in real time and without trial-and-error) the minimum grip force required such that the object will not slip out of robot's hand during manipulation.

The inability to apply gentle grip forces to objects in real time is partially caused by the complexity of achieving adequate "grasps" that would result in adequate object support, and therefore in minimum grip forces required.

Much of the object grasping and manipulation research is directed towards the development of human-like slippage detection and control ability. The robotic grippers developed by most researchers are based on the human hand model, but attempts to reproduce the dexterity and the tactile ability of the human hand have met with many challenges.

This work presents an object grasping and manipulation solution that has nowhere-near the ability of a human hand. However, it is a practical solution that can be applied to many industrial uses, such as material transfer and assembly operations. A unique application for such a gripper is inserting and removing fragile objects from a heat treatment oven. It is quite challenging for most robotic grippers to control grip forces and slippage while manipulating fragile, red-hot objects in a high temperature oven.

This concept allows the design of grippers using various materials and coatings, which facilitates customization for many challenging applications.

II. GRIP FORCE AND SLIPPAGE CONTROL

A. Working principle

The slippage and grip force control relies on friction between a roller and the shaft on which it slides, and between the roller and the object being manipulated. A gripper design using this working principle is shown in Figure 1.

Using rollers to grip and hold objects is counterintuitive, but it actually works unexpectedly well, mainly because this provides a solution to the challenge of incipient slippage detection.

Incipient slippage is the "tell-tale" sign that slippage is about to occur, giving the robot a chance to correct the grip forces in order to prevent uncontrolled object slippage.

The proposed gripper design detects "incipient slippage" by monitoring the relative motion between two surfaces that are not in direct contact with the manipulated object.

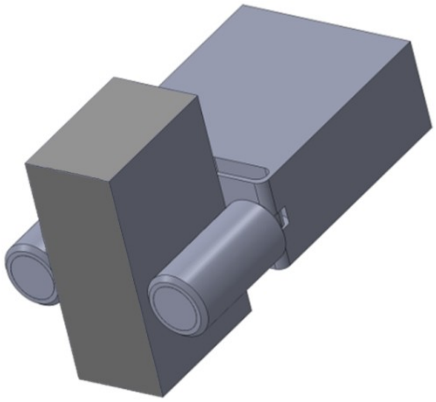

Fig. 1: Friction-base parallel jaw gripper with rollers

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Pavel Dzitac is with the School of Engineering and Built Environment, Central Queensland University Australia, Rockhampton, Australia (phone: +613 92117615; email: pavel.dzitac@cqumail.com).

Abdul Md Mazid is with the School of Engineering and Built Environment, Central Queensland University Australia, Rockhampton, Australia (phone: +617 4930 9672; email: a.mazid@cqu.edu.au).

It is important to note that there are two sets of friction surfaces of interest in this design: one between the gripper roller and the shaft on which it slides, and the other between the gripper roller and the object being manipulated. If there isn't sufficient grip force applied, the roller starts to slip on its support shaft, but still rolls on the surface of the object being manipulated. Therefore this design achieves two important things:

1. Slippage starts between the roller and its support shaft well before slippage between the gripper and the object being manipulated could take place, which in effect achieves incipient slippage detection.
2. Incipient slippage detection allows the controller to apply only the necessary grip force to the object.

While lifting the object, slippage is controlled by applying just sufficient grip force to the object until the roller stops rotating. When the roller stops it means that the grip force is sufficient, and therefore no more grip force is applied.

During gripper acceleration the roller may start to rotate again, meaning that the grip force is too low and the manipulated object is likely to slip. In this case the robot adjusts the grip force again so that the object does not slip out of the gripper during manipulation, while ensuring that the maximum allowable grip forces are not exceeded.

Once the robot knows the minimum grip force required to hold the object it can estimate the mass of the object and adjust the grip force proportionally to the gripper acceleration.

The maximum grip forces can be limited in the robot controller. This in turn automatically limits the maximum gripper acceleration that the robot can use.

B. Design

Originally, a basic gripper as shown in Figure 1 was designed to remove fragile objects from a high temperature heat treatment oven. The rollers can be manufactured of various materials such as ceramic for high temperature applications. The friction surfaces can be coated with various coatings to achieve desired coefficients of friction and gripper performance.

A variation of this design is shown in Figure 2. Both designs are suitable for use in a normal industrial environment for manipulating objects for the purpose of performing assembly and material handling operations. Ingress prevention seals can be fitted to the rollers to prevent contamination of the internal friction surfaces.

When an object is lifted using a gripper such as that in Figure 1, even though the rollers may rotate slightly and the object would move in the downward direction, the object is still under controlled grasp because the roller-displacement feedback allows the robot to know the actual position of the object. This assumes that the object does not rotate in the gripper, which would require vision to determine the new position of the object.

The gripper design in Figure 2 improves the usefulness of the gripper, particularly for smaller objects that can be grasped such that the object is constrained in two axes and therefore can slide only along one axis. This allows the gripper to detect object displacement reliably because object displacement will cause roller rotation, which will allow the controller to detect incipient slippage.

Because the roller keeps rolling along the manipulated object without slippage the amount of displacement can be measured and then compensated by the motion controller.

As mentioned earlier, the gripper design is based on cylindrical rollers that slide on a support shaft. A motion sensor (encoder) is used as a slippage feedback device that monitors the relative motion between the roller and its support shaft, and provides this information to a grip force and slippage controller (a Programmable Logic Controller was used). Other means of detecting motion can be used [2].

During object lifting the grip force is increased until the roller stops rotating and the gripper can lift the object. This happens very fast and the roller rotation is almost unnoticeable. During a typical object lift attempt the time during which the roller rotates is in the range of a few milliseconds.

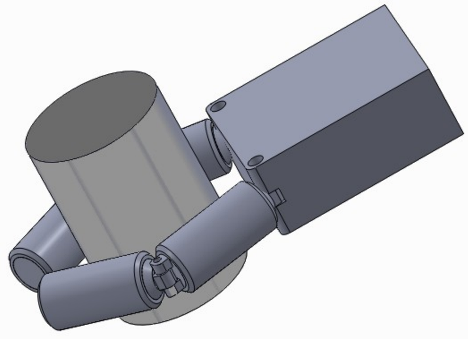

Fig. 2: Robot fingers equipped with friction rollers

The rate of grip force application is proportional to the grip force error, which is proportional to the rotation speed of the roller.

$$\textbf{\textit{Rate of grip force application}} \propto \textbf{\textit{Grip force error}} \tag{1}$$

$$\textbf{\textit{Grip force error}} \propto \textbf{\textit{Roller rotation speed}} \tag{2}$$

$$\textbf{\textit{Rate of grip force application}} \propto \textbf{\textit{Roller rotation speed}} \tag{3}$$

If the coefficient of friction $\boldsymbol{\mu_1}$ (Figure 3) between the roller and the shaft is similar to the coefficient of friction $\boldsymbol{\mu_2}$ between the roller and the manipulated object, when a small grip force is applied and the gripper attempts to lift the object, slippage will start between the roller and its support shaft, but the roller will keep rolling on the object surface without slippage. In this case this is due to the difference between the radius of the shaft and that of the roller.

If the shaft and the inside of the roller are coated with PTFE (Teflon), which will result in both the static coefficient of friction μ_s and dynamic coefficient of friction μ_k to be approximately the same, the grip force necessary to stop roller rotation will be close to that when roller is stationary. If μ_k is lower than μ_s there will be more grip force required to stop the roller from sliding on the shaft than would be required to hold the roller stationary. This is undesirable because the objective of object grasping is to apply only sufficient grip forces to avoid object slippage.

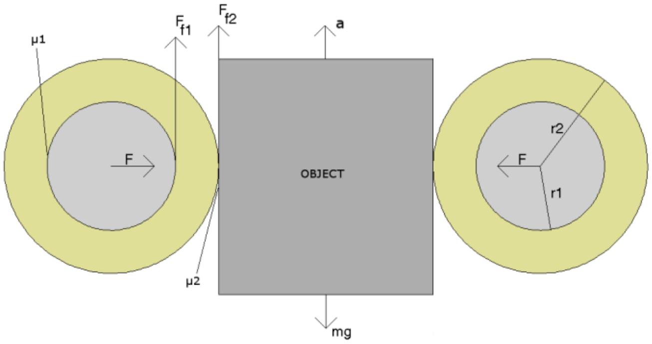

Fig. 3: Gripper forces and coefficients of friction

In Figure 3 the friction force between the roller and its support shaft is given by

$$F_{f1} = \mu_1 F \tag{4}$$

The friction force between the roller and the object prevents roller slippage on the object surface and is given by

$$F_{f2} = \mu_2 F \tag{5}$$

Radius r_1 is always smaller than r_2. The friction torque at the shaft-roller interface is given by

$$T_{f1} = r_1 F_{f1} \tag{6}$$

When the friction force F_{f2} is less than $m(g+a)$, the maximum opposing torque applied at the roller-object interface is limited by the friction force F_{f2} and is given by

$$T_{f2} = r_2 F_{f2}, \qquad F_{f2} < m(g+a) \tag{7}$$

where a is the robot arm acceleration vector.

When the friction force F_{f2} is greater than $m(g+a)$, the opposing torque applied at the roller-object interface is produced by the mass m of the object multiplied by the sum of acceleration forces $(g+a)$ on the object. This torque is given by

$$T_{f2} = r_2 m(g+a), \qquad F_{f2} \geq m(g+a) \tag{8}$$

The net torque between the shaft and roller will be given by

$$T_{net} = T_{f2} - T_{f1} \tag{9}$$

Slippage between the shaft and the roller will begin when the net torque $T_{net} > 0$.

The coating of the roller and the shaft can be selected such as to achieve a desired coefficient of friction, which in conjunction with shaft and roller diameter selection can be used to minimize the net torque T_{net}, and therefore minimize the additional grip force necessary to prevent slippage between the shaft and the roller.

In general, a smaller difference between the shaft and roller diameters will result in a smaller net torque T_{net}, and therefore less unnecessary grip force will be applied.

This simple design concept allows the potential slippage between the roller and the manipulated object to be prevented, and therefore reliable control can be achieved because there is no uncontrolled slippage taking place. The linear displacement of the object s_{object} is always known, and is proportional to the amount of slippage between the roller and the shaft s_{slip}.

$$s_{object} \propto s_{slip} \tag{10}$$

The linear slippage displacement s_{slip} is equal to the arc length of the relative rotation between the shaft and the roller

$$s_{slip} = (\theta/180)\, r_1 \pi \tag{11}$$

The linear displacement of the object during slippage between the shaft and the roller is

$$s_{object} = s_{slip} + ((\theta/180) * (r_2 - r_1)\, \pi) \tag{12}$$

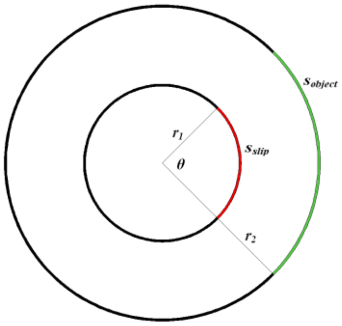

Fig. 4: Object displacement during slippage between the shaft and the roller

C. *Rolling resistance*

The system of forces is more complex in reality that those shown in Figure 3 because rolling resistance [1, 3] is also present in this situation. The rolling resistance will be negligible if the contact surfaces are hard and do not deform significantly during rolling.

However, if the outside of the roller is coated with a soft layer such as rubber, the rolling resistance will not be negligible, particularly for higher grip forces. The rolling resistance reduces the effect of the net torque T_{net} and if too large will allow the object to slip without rotating the roller.

When both, the roller and the object are hard and do not deform much, the effective radius a (Figure 5) is approximately equal to the roller radius r. However, if the roller or the object is softer, the deformation will be larger and rolling resistance will be significant.

The rolling resistance F_{roll} is given by

$$F_{roll} = C_{rr} F \tag{13}$$

where C_{rr} is the rolling resistance coefficient and F is the grip force applied.

The rolling resistance coefficient, C_{rr} is given by

$$C_{rr} = ((r-a)/2r)^{1/2} \tag{14}$$

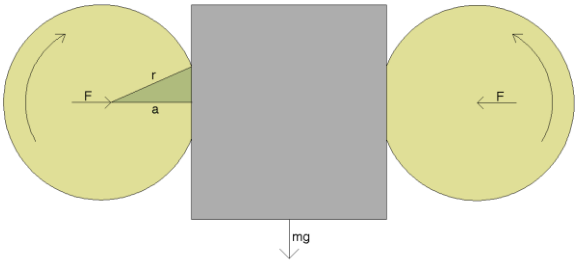

Fig. 5: Rolling resistance due to roller deformation

D. *Design considerations*

For the roller-based gripper to control slippage and grip forces correctly the following should be considered:

1. Ideally the static and dynamic coefficients of friction should not be greatly different ($\mu_s \approx \mu_k$). The smaller the difference the better.
2. A smaller coefficient of friction between the shaft and the roller results in higher sensitivity to slippage, but also requires larger grip forces to avoid slippage between the shaft and the roller.
3. A larger difference between the shaft and roller radius results in higher sensitivity to slippage, but also requires larger grip forces to avoid slippage between the shaft and the roller.
4. The torque at the shaft-roller interface should be less than the torque at the roller-object interface, otherwise the object will slip without rotating the roller and therefore slippage will not be detected.

$$r_1 F_{f1} < T_{f2} \tag{15}$$

5. The rolling resistance should be small enough not to affect the slippage sensing

$$(F_{f2} - F_{roll})\, r_2 > F_{f1}\, r_1 \tag{16}$$

If the rolling resistance is too large the object will slip without rotating the roller, and therefore slippage will not be detected.

E. *Factors that affect friction*

Because the proposed gripper design is based on friction it is worth having a quick look at some factors that affect friction, particularly those that would be encountered in the propose gripper design.

The friction phenomenon is still not well understood, but it is generally accepted that friction is the effect of the interaction of two surfaces at macroscopic and microscopic levels. Probably the most counterintuitive fact about friction is that it does not depend on the (apparent) contact surface area of the object. It is generally accepted that friction is proportional to the normal force, or load, that presses the two surfaces together [10-13].

At macroscopic level, the surface artifacts interact with each other and oppose the relative motion between the two surfaces. The surface artifacts are made up of peaks and valleys, which make up the roughness and the waviness of the surface. Together, the surface roughness and waviness make up the texture of the surface [4] as shown in Figure 6.

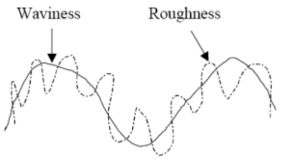

Fig. 6: Object surface texture

At microscopic level, molecular interaction such as adhesion causes additional resistance to sliding of two surfaces relative to each other. The type of material, temperature, lubrication and surface oxidation (which acts as a film of lubricant) of the two materials in contact with each other have additional effects on friction [10-12].

Two high precision flat surfaces, such as those of high precision gauge blocks used in metrology, are known to “stick” to each other and resist separation by sliding. In this case roughness plays a smaller role in the friction between the two surfaces, which suggests that there is significant interaction at molecular level.

Lubricating the interacting surfaces reduces the friction, mainly by separating the two surfaces such that the surfaces interact with the film of lubricant, and not directly with each other. Un-lubricated surfaces can have stray “lubricants” such as surface oxidation, contaminants, or gasses that have been release during friction and trapped between the two surfaces in contact [10-13].

Materials behave differently at different temperatures. In some materials increased temperature causes an increase in friction, which is one of the reasons why racing cars warm up their tires before the race. Other materials such as some polymers experience non-linear friction with increase in temperature [10-13].

Friction between some materials decreases once the two surfaces are in relative motion, which is the basis for the difference between the static and dynamic coefficients of friction. Some materials such as PTFE (Teflon) have almost identical static and dynamic coefficients of friction [10-13].

The dynamic coefficient of friction, μ_{k}, is also speed-dependent. For many materials, μ_k decreases with speed [13].

It should be noted that the coefficients of friction found in technical literature and standards are approximate values because the actual coefficient of friction is dependent on many factors, and can vary even for the same material [10-13].

Given the complexity and uncertainty of the friction phenomenon, as briefly discussed above, the most reliable way to determine the coefficient of friction for specific material combinations and application is to use a coefficient-of-friction measurement machine, which is typically available in mechanical engineering laboratories.

III. RESULTS

Initial proof of concept testing was performed to determine whether a roller-based gripper would behave as predicted theoretically.

After reviewing factors that affect friction, as reviewed above, it was evident that the actual performance of the roller-based gripper may be somewhat different from the expected theoretical behavior.

Rollers, made of solid PTFE, were built and fitted to a custom parallel gripper as shown in Figure 7. The rollers were designed with a wall thickness of 5mm to avoid the results being significantly affected by roller deformation.

A special object (split-block) was designed and built for the object lifting experiment as shown in Figure 7. The block is split in the middle along the vertical.

Two horizontal guide pins inside the split-block allow the two split-block sections to move horizontally in a parallel fashion with minimum friction and interference to facilitate measurement of grasp force.

A force sensor was placed between the two split-block sections to allow the gasp force to be measured directly as experienced by the split-block when it is grasped and lifted. This simplifies the measurement of the grasping force because it is not measured indirectly through robot finger linkages.

A miniature pulse encoder was connected to one roller and used as input to the robot controller to allow the robot to control the grasp force based on the movement of the roller. The pulse encoder used has a resolution of 1000 pulses per revolution. This translates to a roller rotation detection resolution of 0.3 degrees. For precision slippage detection an encoder with a resolution of 3000 pulses per revolution would have been more desirable.

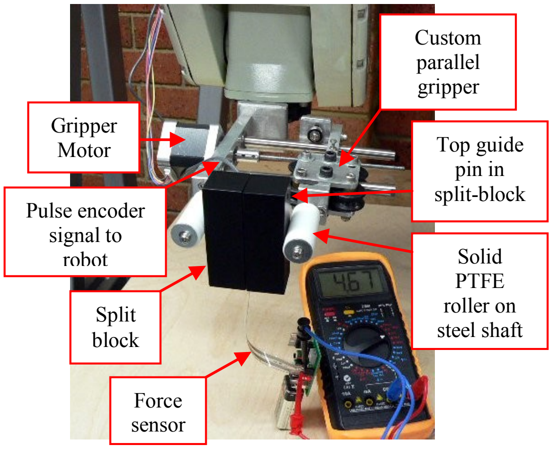

Fig. 7: The object lifting experiment setup using roller-based gripper

Experimentation results showed that the minimum grasp force required to prevent object slippage in the gripper was close to the predicted value. Table I the experimental results for holding force required to prevent object slippage. The experimental grasp force results are shown relative to the theoretically predicted grasp force values.

The steel shafts of the parallel gripper have a diameter of 10mm, while the PTFE roller has an inner diameter of

10.1mm and an outer diameter of 20mm. The split block has a mass of 0.3kg.

TABLE I
GRASP FORCE RESULTS – PTFE ON STEEL @ 23°C

Grasp attempt	Theoretical Value (N)	Experimental Value (N)
1	58	48.5
2	58	48.3
3	58	48.2
4	58	48.1
5	58	48.2

For the calculation of the theoretical value it was assumed that PTFE against steel has a coefficient of friction of 0.05. However, the experimentation results show that the actual coefficient of friction between PTFE and steel in this case was around 0.06. This may be due to differences between the estimated and actual surface finishes, actual material properties, and potentially some surface contamination.

IV. CONCLUSION

This concept is deceptively simple but provides a solution to object slippage prevention that has proven to be a serious challenge in robotics.

Experimentation was carried out with other shaft and roller materials including solid PTFE shaft and rollers. Most materials work fine, but the low coefficients of friction such as that of PTFE require higher grip forces.

Further investigation and work is being done using this concept, including the development of a prototype robot hand with articulated fingers, each with three joints (similar to Figure 2), for testing the effectiveness, sensitivity and reliability for grasping and slippage control.

This grasp force and slippage control design has the potential to yield a robust, rugged and relatively sensitive robot hand that could be used for a wide range of loads in a variety of environments.

The main weakness of this gripper design is that it detects slippage in only one axis. Further work is needed to add slippage detection capability in the other axes.

It is expected that a robot hand equipped with such fingers will not be capable of detecting slippage in all possible situations, but could provide a solution to object slippage control in many applications.

REFERENCES

[1] R.C. Hibbeler, Engineering Mechanics: Statics & Dynamics (Eleventh ed.), Pearson, Prentice Hall, 2007.

[2] M. Tresanchez, T. Palleja, M. Teixido, and J. Palacin, The optical mouse sensor as an incremental encoder, Sens. Actuators A, Phys., vol. 155, no. 1, pp. 73–81, Oct. 2009, DOI:10.1016/j.sna.2009.08.003.

[3] M. Sönmez, A Study on the Combined Effect of Axle Friction and Rolling Resistance, The International Journal of Mechanical Engineering Education, Vol.31, No.:2, Manchester University Press, April 2003.

[4] M. A. Mazid and R.A. Russell, A Robotic Opto-tactile Sensor for Assessing Object Surface Texture, in Proc. IEEE Int'l Conf. on Robotics, Automation and Mechatronics (RAM 2006). Bangkok, pp. 387-391, 2006.

[5] A. Bicchi, J. K. Salisburry, and D. L. Brock, Experimental evaluation of friction characteristics with an articulated robotic hand, in Proceedings of Int'l Symposium Experimental Robotics, Toulouse, France, 1991.

[6] Somak Petchartee, and Gareth Monkman, Pre-slip detection based Tactile Sensing in Proc. of Int'l Conf. on Sensors, Sensor Networks, and Information, 3-6 December, 2007.

[7] J.S. Wilson (editor), Sensor Technology Handbook, Burlington, MA, Newnes, 2005.

[8] E. Oberg, F.D. Jones, H.L. Horton, H.H. Ryffel, Machinery's Handbook, 25th ed., Industrial Press, New York, 1996.

[9] Introduction to Engineering and Statics: Friction, Division of Engineering, Brown University, Available: http://www.engin.brown.edu/courses/en3/Notes/Statics/friction/friction.htm

[10] E. Rabinowicz, Friction and Wear of Materials, 2nd Edition, Wiley & Sons Inc., 1995.

[11] F. P. Bowden and D. Tabor, The Friction and Lubrication of Solids, Oxford Science Press, UK, 1986.

[12] V. L. Popov, Contact Mechanics and Friction: Physical Principles and Applications, 1st ed. Springer-Verlag: Berlin, Heidelberg, 2010.

[13] H. Rothbart, T. H. Brown, Mechanical Design Handbook, Second Edition: Measurement, Analysis and Control of Dynamic Systems, McGraw-Hill Professional, 2006.