The Effective Radius and Resistance to Slippage

Pavel Dzitac[1], Abdul Md Mazid[2], Guy Littlefair[1] and Ashwin Polishetty[1]
[1]School of Engineering, Deakin University, Geelong, Australia
[2]School of Engineering and Technology, Central Queensland University, Rockhampton, Australia

Keywords: Gripper Design, Slippage Control, Manipulation Reliability.

Abstract: This work reveals that parallel gripper flat-jaw configuration affects grasping effectiveness. An important finding is the fact that object grasp reliability is influenced significantly by gripper's ability to develop high resistance to object rotation in the gripper. The concept of effective torque radius, which increases resistance to object rotation in the gripper, is presented here and can be extrapolated to other grasping devices and grasping strategies to improve their reliability and make them more effective. Grippers with full-jaw contact surface and those with discrete contact areas have been investigated using simple experimental setups. Essential mathematical models needed for analytical investigation, based on simple mechanics for full-jaw contact surfaces and discrete-jaw contact surfaces, are presented. These may be useful for gripper jaw design purposes.

1 INTRODUCTION

Robotic parallel grippers, used in many real-life applications have to grasp and manipulate a variety of small and large objects safely.

An important requirement in safe object grasping and manipulation is reliability, which can be assessed via some quality measures (Chinellato et al., 2004; Morales et al., 2004). There are many possible views as to what constitutes "reliable" object grasping and manipulation (Chinellato et al., 2004; Morales et al., 2004; Flanagan et al., 2004; Diankov et al., 2009; Ciocarlie et al., 2010).

There are also many factors that influence object manipulation reliability (Dzitac and Mazid, 2013); the configuration of gripper jaws is one of them. As a result of correct gripper jaw configuration it is also possible to reduce the required grasp forces and therefore the energy necessary to grasp and manipulate an object.

This paper uses a paralle gripper to show how a flat gripper jaw design and its object grasping strategy can be modified and to increase resistance to object slippage by increasing griper's resistance to object rotation in the gripper. These concepts are applicable to most robotic grasping devices.

2 ANALISYS

It is known from automotive disk braking technology used in modern vehicles that the effective torque radius r_e of the brake pads, together with the coefficient of friction μ between the brake pads and brake disk, and the normal force F applied to the brake pads determine the braking torque capacity T of the braking system (Budynas and Nisbett, 2006).

$$T = \mu F r_e \tag{1}$$

The effective torque radius r_e of a brake pad is given by

$$r_e = \frac{1}{2}(r_o - r_i) \tag{2}$$

Where, r_o is the outside radius of the brake pad and r_i is the inside radius of the brake pad relative to the axis of rotation of the brake disk (Budynas and Nisbett, 2006).

Equation 1 implies that a parallel gripper with longer jaws has a higher torque capacity than a parallel gripper with short jaws due to a larger effective torque radius r_e.

For a flat parallel gripper that is grasping a flat object, the effective torque radius r_e can be estimated as

Dzitac P., Mazid A., Littlefair G. and Polishetty A..
The Effective Radius and Resistance to Slippage.
DOI: 10.5220/0005048103960401
In *Proceedings of the 11th International Conference on Informatics in Control, Automation and Robotics* (ICINCO-2014), pages 396-401
ISBN: 978-989-758-040-6

$$r_e = \frac{1}{2}\left(\frac{L}{2} + 0\right) = \frac{L}{4} \quad (3)$$

Where, L is the gripper jaw length.

The flat jaws of a parallel gripper have been modified to contain discrete grasp surfaces referred to as "pads" in this paper, and used to test their influence on the effective torque radius as shown in Figure 1. The pads are formed by machining a recess at the centre of the gripper jaw contact surface such that only the pads are in contact with the object.

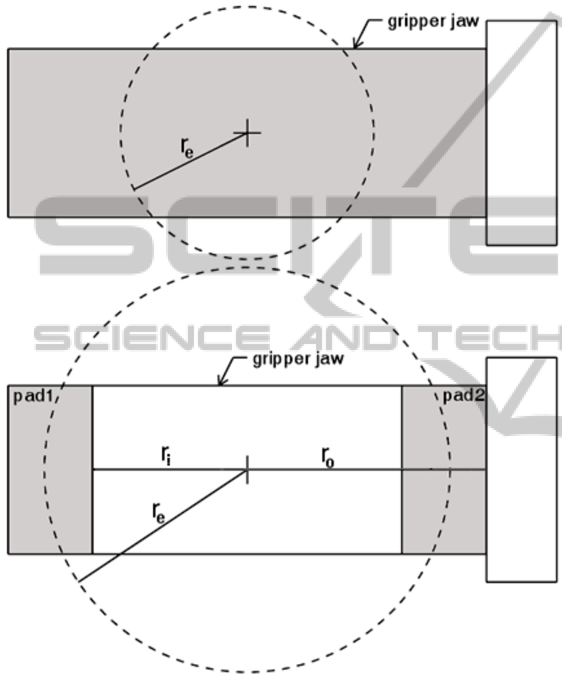

Figure 1: Comparison of effective torque radius r_e for a gripper with full jaw contact surface and a gripper with discrete pad contact areas.

Notice that for the same gripper jaw length, the gripper with discrete pad contact areas has a larger effective torque radius r_e than the gripper with full jaw contact surface. In this jaw design the effective torque radius can be increased by increasing the distance from the centre of the jaw to the centre of the pad. Equation 1 can be used to estimate the torque radius r_e of the jaw with pads shown schematically in Figure 1 (bottom sketch).

The following analysis attempts to show that the choice of grasp point locations influences not only the object stability during object manipulation but also the grasp force required.

For simplicity the parallel gripper with pads is used to explain this concept. The sketch in Figure 2 shows the parallel gripper with pads holding a flat bar in horizontal orientation. The force, *mg,* at the centre of the flat bar develops a moment M_{bar} at the centre of the gripper that is given by

$$M_{bar} = mgd \quad (4)$$

Where, m is the mass of the flat bar, g is the gravitational acceleration and d is the distance from the centre of gravity of the flat bar to the centre of the gripper jaw.

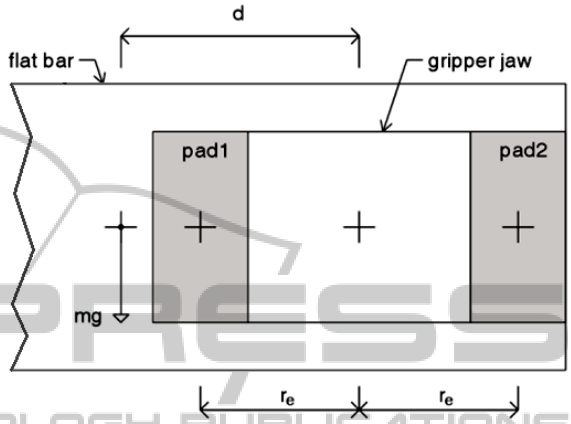

Figure 2: Gripper jaws fitted with pads holding a flat bar.

Each of the gripper jaws must develop equal and opposing moments in order to keep the flat bar from rotating in the gripper jaws, plus additional reaction forces necessary at each pad to support a share of the flat bar weight.

The required minimum opposing moment at the gripper M_{grip} is given by

$$M_{grip} = mgd = 2F_c r_e \quad (5)$$

Where, F_c is the force couple necessary to counteract the moment M_{bar}, and is given by

$$F_c = \frac{mgd}{2r_e} \quad (6)$$

Note that the gripper has two opposing jaws that develop friction reaction forces on two independent flat bar surfaces and therefore each gripper jaw has to develop only sufficient reaction forces to support half of the weight of the flat bar.

For clarity, the analysis is done on one jaw only and therefore only half of the actual applied force to the gripper is used in the analysis. As a result each pad has to develop a reaction force F_{mg} given by

$$F_{mg} = \frac{0.5\, mg}{2} = \frac{mg}{4} \quad (7)$$

Figure 3 shows the free body diagram of the gripper in Figure 2. The forces acting on one gripper jaw are the moment $\mathrm{M_{bar}}$, the weight of the flat bar supported by one jaw (mg/2), and the reaction forces (force couple F_c and the reaction force F_{mg} at each pad supporting the weight of the flat bar).

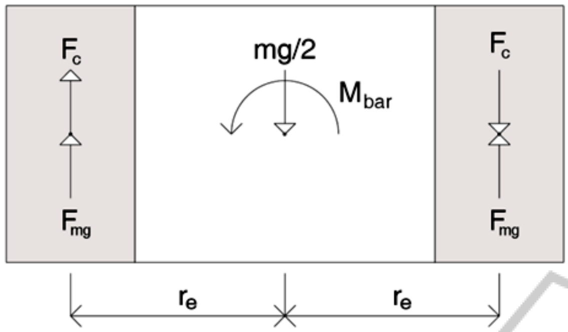

Figure 3: Free body diagram of gripper with pads.

The net reaction forces, F_{r1} at gripper "pad1" and F_{r2} at gripper "pad2" respectively, are given by

$$F_{r_1} = F_c + F_{mg} = \frac{mgd}{2r_e} + \frac{mg}{4} \quad (8)$$

$$F_{r_2} = F_c - F_{mg} = \frac{mgd}{2r_e} - \frac{mg}{4} \quad (9)$$

It can be seen from Equations 8 and 9 that the required reaction force at "pad1" is greater than that at "pad2" by *mg/2*.

Considering this fact, it is expected that slippage and therefore loss of grasp control is most likely to occur at "pad1" first, even though the same grasp force is applied to both gripper pads. The expected behaviour has been tested by gradually decreasing the grasp force on the flat bar until slippage is noticed. It has been confirmed that for the grasp configuration shown in Figure 2, slippage starts at "pad1" first.

It can therefore be concluded that holding a flat bar with the gripper in horizontal orientation is not an optimum solution. However, most common object grasping and manipulation in industry, using parallel grippers, is done this way.

The minimum static gripper force F_s that needs to be applied to the gripper in Figure 2 to prevent slippage at "pad1" is given by

$$F_s = \frac{Fr_1}{\mu_s} \quad (10)$$

Where, μ_s is the static coefficient of friction between the gripper pads and the flat bar.

A different gripper configuration is presented in Figure 4. In this configuration the gripper jaws are still the same as in the previous design, but in this case the jaws are in vertical orientation relative to the flat bar.

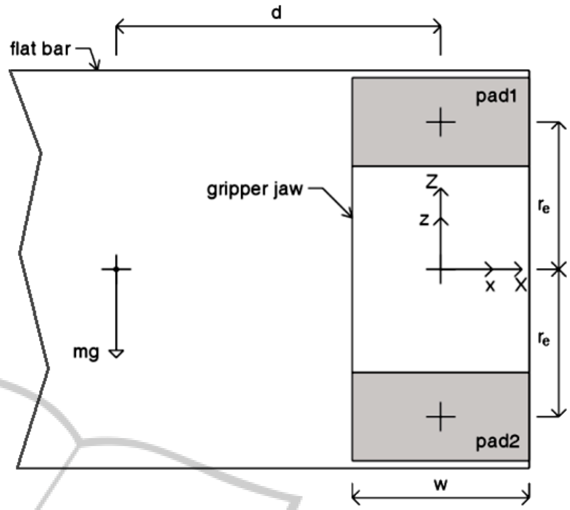

Figure 4: Gripper with vertical jaws.

Figure 5 shows the free body diagram of the gripper with vertical jaws from Figure 4. The forces acting on one jaw of the gripper are the moment M_{bar}, the weight of the flat bar supported by one jaw (*mg/2*), and the reaction forces (force couple F_c and the reaction force F_{mg} at each pad supporting the weight of the flat bar).

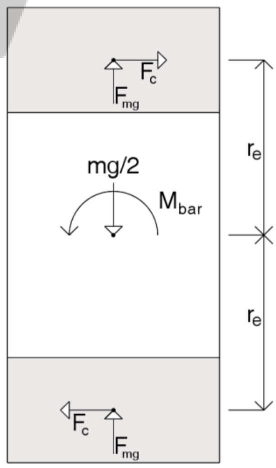

Figure 5: Free body diagram of gripper with vertical jaws.

In this configuration the force *mg/2* acts equally through both gripper pads. The force couple also acts through the gripper pads as before, resulting in equal forces being applied to both. The resultant reaction vectors F_{r1} and F_{r2} at the two gripper pads are shown in Figure 6 and are given by

$$F_{r_1} = \left(F_c^2 + F_{mg}^2\right)^{\frac{1}{2}} \quad (11)$$

$$F_{r_2} = \left(F_c^2 + F_{mg}^2\right)^{1/2} \tag{12}$$

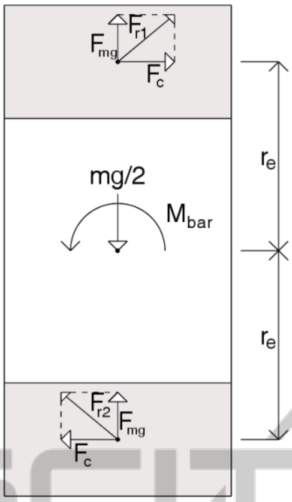

Figure 6: Resultant vectors F_{r1} and F_{r2}.

In this gripper configuration the forces on the object are smaller and equal at both pads. This means that the gripper has to apply a smaller overall grasp force to hold the object successfully, which in turn means that a fragile object can be held safer in this gripper configuration. Consequently this gripper requires less energy and has a longer useful life.

To help illustrate the concept of effective torque radius only static analysis has been used in this paper. However, for a moving gripper, dynamic forces must be considered. Although not discussed here in detail, the dynamic force components acting on the gripper are given below with respect to gripper coordinates x, y, z (Figure 4).

- The F_x component acts along the x axis and tends to pull the object out of the robot gripper;
- The F_y component acts along the y axis to "wedge" the gripper open;
- The F_z component acts along the z axis and produces object rotation tendency at the centre of the gripper.

$$F_x = mg(sin\theta) + ma(cos\alpha)(sin\beta) \tag{13}$$

Where, α is the "altitude" angle from the XY plane and β is the "azimuth" angle from the XZ plane, at which the gripper acceleration vector a acts (XYZ are world coordinates).

$$F_y = mg(\sin\phi)\left(\frac{(d-w)\cos\theta}{w}\right) + ma(\cos\alpha)(\cos\beta) \tag{14}$$

Where, ϕ is the angle of the gripper when gripper is rotated around X world coordinate, θ is the angle when gripper is rotated around the Y world coordinate, and w is the horizontal width of the gripper in Figure 4.

$$F_z = \left(\frac{mg(\cos\phi) + ma(\sin\alpha)d(\cos\theta)}{2r_e}\right) + \left(\frac{mg(\cos\phi) + ma(\sin\alpha)}{4}\right) \tag{15}$$

Note that F_x and F_z combine into a larger net resultant force F_R acting in the xz plane, and is given by

$$F_R = [F_x^2 + F_z^2]^{\frac{1}{2}} \tag{16}$$

For reliable object manipulation the gripper must develop a reaction force equal to or greater than the largest force that pulls the object out of the gripper or acts to "wedge" the gripper open.

The experiments and observations in this project indicate that higher resistance to object rotation in the gripper contributes to object manipulation reliability.

However the benefits of improved gripper mechanical ability can only be maximised when used in conjunction with adequate manipulator intelligence, which is necessary to make better grasp decisions and manipulate the object in such a way as to avoid gripper weaknesses, while making the most of its strengths.

3 EXPERIMENTATION AND RESULTS

To test the above described concept, a flat disk made of Acetal has been grasped using a spring-loaded parallel gripper, equipped with flat jaws made also of Acetal. Two pairs of flat jaws of different sizes are illustrated in Figure 7. The experimental setup is illustrated in Figures 8 and 9. The experimentation carried out in this section is not aimed at high accuracy results but rather to demonstrate the difference in the effective torque of short flat jaws compared to long flat jaws.

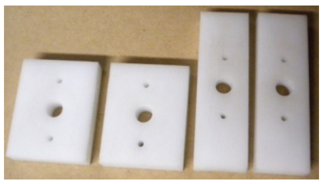

Figure 7: Short and long flat jaws made of Acetal.

The experiment with short flat jaws, as shown in Figure 8, has been carried out as follows:

- The 50mm long jaws were mounted on the gripper plates (either side of the 86mm disk) and clamped using a centre screw, spring, washer and force adjustment nut.
- The spring compression required to produce a force of approximately 70N has been determined by compressing the spring on calibrated digital scales and measuring the compressed spring length that produced 70N. The spring compression has then been replicated on the gripper setup by adjusting the nut until approximately the same spring compression has been achieved.
- The disc has been rotated by applying a tangential force to the disc using a force gauge and a string attached to the disk such as to maintain the axis of rotation of the disk at the centre of the jaws.
- The force required to cause the disk to slip has been recorded five times and an average has been calculated and recorded in Table 1.

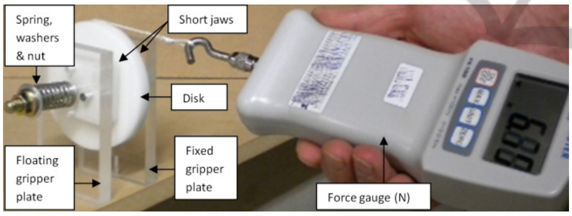

Figure 8: Spring-loaded gripper with 50mm flat jaws.

The same experimental procedure has been followed for the experiment in Figure 9, except that in this case the long jaws were used instead of the short ones.

It has been noticed that for the same clamping force, a slightly larger force is required to cause disk slippage when it is held in the gripper fitted with long jaws than when it is held in the gripper fitted with short jaws.

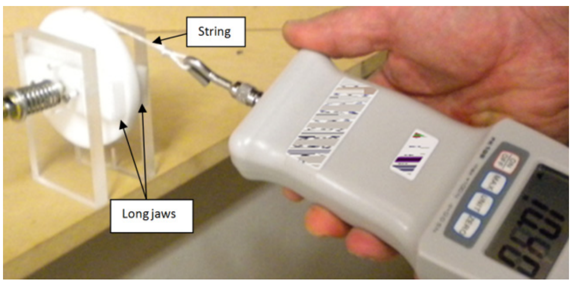

Figure 9: Spring-loaded gripper with 80mm jaws (flat side is gripping the disc).

The experimental results are summarised in Table 1. Both, the short and long jaws used for experimentation had approximately the same total contact surface area.

Table 1: Effective torque radius experiment – short and long gripper jaws without pads.

Jaw length (mm)	Effective radius (mm)	Force applic. radius (mm)	Clamp force (N)	Average slip force (N)
50	25	43	70	7.1
80	40	43	70	10.3

The results in Table 1 agree with the concept of effective torque radius (Budynas and Nisbett, 2006), which is influenced more by how the contact area is distributed rather that the size of the contact surface area.

In both cases the inside radius r_i is assumed to be equal to 0mm and therefore the effective torque radius is assumed to depend only on the outside radius r_o of the jaw, which in turn is assumed to be equivalent to half of the jaw length.

It is also assumed that the applied grasp force is evenly distributed at each of the two gripper jaws.
To test the gripper pad principle the long jaws were machined such as to obtain two discrete pads on each jaw as shown in Figure 10.

Figure 10: Long jaws with pads.

The same experimental procedure has also been carried out for the long jaws with pads as that described for Figure 9, except the jaw pads were now gripping the disk as shown in Figure 11.

Figure 11: Spring-loaded gripper jaws with the pads gripping the disc.

Five samples of pull forces necessary to cause disk slippage in gripper jaws with pads were averaged and recorded in Table 2.

The additional pull force required to cause disk slippage is significantly larger, which confirms that jaws with discrete peripheral pads result in a larger effective torque radius r_e than flat jaws without peripheral pads.

Table 2: Effective torque radius experiment – long flat gripper jaws with pads.

Jaw length (mm)	Effective radius (mm)	Force applic. radius (mm)	Clamp force (N)	Average slip force (N)
80	30	43	70	16.9

Just like in the previous experiments, the experimentation carried out here is not aimed at high accuracy results but rather to highlight the difference in the effective torque radius of jaws with pads compared to jaws without pads.

4 CONCLUSION AND FUTURE WORK

While performing object grasping and manipulation experiments it was noticed that object manipulation reliability was influenced significantly by the ability of a parallel gripper to develop optimum reaction forces at all grasp points. It was found that this ability was dependent on the ability to resist object rotation in the gripper, which in turn was dependent on the gripper design and the locations of grasp points on the grasped object.

Equal load sharing by all grasp points resulted in higher resistance to slippage. When one grasp point was holding a higher share of the load it was more likely to slip during manipulation.

A modified gripper jaw design and grasping strategy that together offered a higher resistance to object rotation in the gripper and minimised the required grasp forces was also proposed.

It is believed that the concept of effective torque radius presented here can be extrapolated to other gripper types and grasping strategies to improve their reliability and effectiveness.

The concepts in this paper are applicable to most object grasping devices that create contact points with the object, including multi-finger humanoid hands.

Future work can be done to develop designs and grasping strategies for multi-finger robotic grasping devices that would increase their resistance to object rotation and therefore minimise the effect of torsional forces at the object-gripper interface that contribute to object slippage.

REFERENCES

Chinellato, E., Morales, A., Fisher, R.B., del Pobil, A.P., 2004. Visual quality measures for characterizing planar robot grasps. In *IEEE Trans. Systems, Man and Cybernetics - Part C: Applications and Reviews, pp. 30–41*.

Morales, A., Chinellato, E., Fagg, A.H., del Pobil, A., 2004. Using experience for assessing grasp reliability. In *International Journal of Humanoid Robotics,* vol. 1, no. 4, pp. 671–691.

Flanagan, J.R., King, S., Wolpert, D.M., Johansson, R.S., 2001, Sensorimotor prediction and memory in object manipulation. In Canadian Journal of Experimental Psychology, no. 55, vol. 2, pp. 87 - 95.

Diankov, R., Kanade, T., Kuffner, J., 2009. Integrating grasp planning and visual feedback for reliable manipulation. In *IEEE/RAS International Conference on Humanoid Robots (Humanoids)*, pp. 646–652.

Ciocarlie, M., Hsiao, K., Jones, E. G., Chitta, S., Rusu, R. B., Sucan, I. A., 2010, Towards reliable grasping and manipulation in household environments. In *International Symposium on Experimental Robotics*, New Delhi, India, pp. 241-252.

Dzitac, P., Mazid, A. M., 2013. Factors that influence reliable object manipulation. In *Proceedings of the IEEE Industrial Electronics and Applications International Conference (ICIEA)*, Melbourne, Australia, pp. 1468-1473.

Budynas R. G., Nisbett, J.K., 2006. *Shigley's Mechanical Engineering Design (8th Ed.)*, McGraw-Hill, pp. 826-829.