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A NOVEL GRIPPING SYSTEM FOR DELIVERY OF PACKAGES VIA UNMANNED AERIAL VEHICLES

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ABSTRACT

An Unmanned Aerial Vehicle (UAV) can carry packages to locations that are unreachable by a ground vehicle using a gripper that can handle standard sized packages. This paper presents a UAV-mounted system for grasping corrugated boxes. The proposed gripping system uses two pairs of end effectors which are arranged perpendicular to each other. All four grippers are geared so that they can be actuated by a single control input. The mechanism is designed to handle position and orientation errors of the box relative to the gripper. The gripper was experimentally validated using a test box that was misaligned in position and orientation.

Keywords: package delivery drones, robotic gripper, UAV, grasping mechanism.

1. INTRODUCTION

Unmanned Aerial Vehicles have developed a growing interest among researchers because of applications such as disaster management operations [1], assessment of damage to historical buildings and cultural artifacts [2], detection of forest fires [3], and precision agriculture [4].

A special class of UAVs is the four rotor Vertical Takeoff and Landing (VTOL) vehicle called the quadcopter [5]. A VTOL UAV can take off or land on any flat surface without the need for a long runway. A VTOL UAV is an ideal delivery vehicle, especially for medical support [6], electric power to recharge batteries of wireless sensors [7], and packages in the form of corrugated boxes.

Standardized corrugated boxes can be used to pack and ship more than 1,160 products including live fish [8]. Amazon Prime Air (APA) and VertiKUL for Autonomous Parcel Delivery [9, 10] envision delivering packages within 30 minutes from ordering. These UAV designs have a chamber for box storage. The package may be automatically fed into this chamber through a conveyor (APA drone) or it may be manually loaded (VertiKUL drone). The fixed chamber limits the package to one box size, as a smaller package would add dynamic disturbances to the flight. Google used a cable to pull a package up to the base of a drone and lock it underneath the drone for transport [11, 12]. This approach requires a mounting point, such as a hoop, to be included on the box.

The approach described in this paper is a novel robotic gripping system that can be mounted on a UAV. The gripper can grasp and lift packages when the drone maneuvers into a pick-up location. The gripper is designed to minimize the effects of orientation and position errors between the drone and the package.

2. BACKGROUND

Monkman, et al. classify robotic grippers as Impactive, Astrictive, Ingressive, and Contigutive grippers [13]; Mousavi, et al. classify grippers as mechanical grippers, vacuum and magnetic grippers, universal grippers, and multi-fingered hands [14].

Multi-fingered hands [15] or high degree-of-freedom (DOF) manipulators [16] allow a wide variety of shapes to be grasped; however, these grippers require complex control algorithms and inverse kinematic predictions of path. Pneumatic, hydraulic, or vacuum grippers can lift a variety of objects [17], but they require fluid handling systems to generate pressure or vacuum, which may make them unsuitable for a drone application with limited lift capability and on-board power. Hooks [18], cables [19], avian inspired grippers (eagle claw) [20], or magnetic grapples [21], can grasp arbitrarily shaped objects provided that a custom attachment has been designed into the package. The construction of these grippers is simple, and the power and control requirements are minimal. However, precisely positioning the hook to make a grasp can be difficult for a drone,

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and the in-flight changes in the drone's aerodynamics present a difficult control challenge.

One of the most important functions for a drone-mounted gripper is the ability to pick up a package that is misaligned with the drone in position and Euler angles (*pose*) [22]. Goldberg developed a mechanism to align objects using mechanical compliance and no sensors [23]. Mason et al. considered pushing operations [24], and Harada et al. examined alignment during assembly tasks [25].

The gripper presented in this paper uses a differential mechanism to actuate all four end effectors from the same control input, similar to the mechanism in a four-jaw chuck (see Fig. 1). The underactuation introduces operational flexibility and simplifies the control system by reducing the number of independent actuators [26]. Differential mechanisms can be heavy and bulky due to the gearing, but careful design and the use of 3D printing technology allows a light and compact design to be achieved.

Differential mechanisms use different gearing strategies, such as bevel gears and worm and gear, both of which transmit torque at right angles to the motion. A lead screw can convert the rotary motion of an electric motor to the linear motion of the end effector. Lead screws with the proper lead angle can self-lock, which allows the drone to remove power from the actuator until the drone is ready to deposit the package.

The validation of the prototype was performed to determine the effect of package weight, position misalignment, and orientation misalignment.

Position errors were validated using the method described in [27]. A robotic hand was tested to determine if it could grasp an object that had been placed out-of-position in increments of 10 mm in (x, y). A grasp was called successful if the object was lifted 150 mm above the table, and the grasp was considered stable if the object did not slip.

Orientation errors were validated using a method similar to [28]. In their tests, error was defined as the difference between the angular orientations of the circular object and the gripper. For the orientation misalignment tests described in this paper, a rectangular package was used. Initial orientation of the object was randomly selected while the orientation of the gripper was kept constant. Misalignment was tested in spans of 5° up to 45°. The gripper failed when the final angular misalignment of the object was large.

3. MECHANICAL DESIGN

A gripping system that uses two pairs of perpendicularly mounted actuators to move the end effectors is shown in Fig. 1. A motor actuates the drive gear, which is connected to four bevel gears to drive each of the four lead screws in tandem. The lead screws convert the rotary motion to linear motion of the end effectors. The ellipsoidal shaped end effectors and a shuttle which holds the nut for the lead screw are 3D printed in PLA.

During the process of grasping, the end effectors push the wall of the package and hold it from four sides using the surface contact friction force. To increase the coefficient of friction between the end effector and the cardboard box, a rubber coating is attached to the end effector. Experiments were performed with and without this rubber coating to determine the differences. Measurement of the applied force by the end effectors is made using a force sensor that is embedded inside one end effector in each pair. The package is held with the *self-locking* capability of the lead screws. The mechanism is housed in an outer frame for purposes of testing it. The gripper would be connected to the under-side of a drone in use (see Fig. 1 for a CAD model).

Based on classification of grippers discussed earlier [13], the proposed gripper can be classified as an *Impactive gripper*.

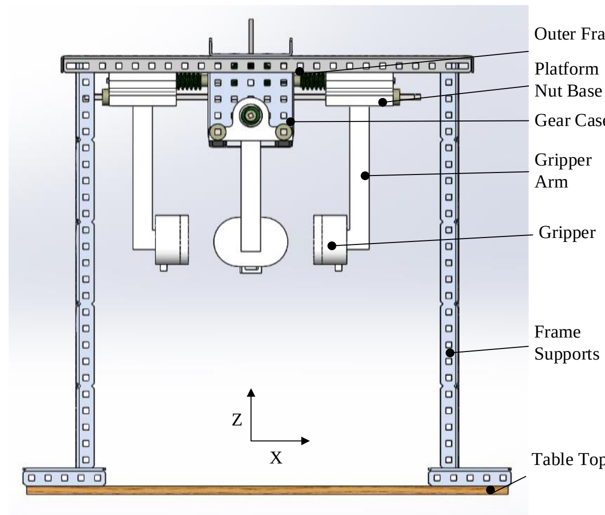

FIGURE 1: CAD Model – Front View

3.1 Functional Requirements

The functional requirements that the gripping system satisfies are:

1. Hold the package with force isotropy.
2. Provide self-locking capability.
3. Handle pose errors automatically without the need of any sensory feedback.
4. Provide sufficient grasp span to accommodate target object.
5. Be light in weight such that it can be mounted on a UAV.

3.2 Grasping Phases

Grasping phases for the gripping system are (see Fig. 2):

a) *Approach Target Object:* This is the first stage where the gripping system is in an open position and the UAV tries to position itself in the near vicinity of the package.
b) *Make Contact:* The grippers are actuated, and first contact with the package is made.
c) *Align/Orient the Box:* The grippers remove misalignment between the gripping system and the package by pushing the package.
d) *Increase Grasping Force:* The grippers increase the grasping force on the package walls until the force sensor reads the desired grasping force.

e) *Lift the Object:* After a successful grasp, the UAV is ready for flight and can take off.
f) *Releasing the Object:* Once the UAV has moved to the desired location and has performed the descent, the grippers are reversed, and the package is released.

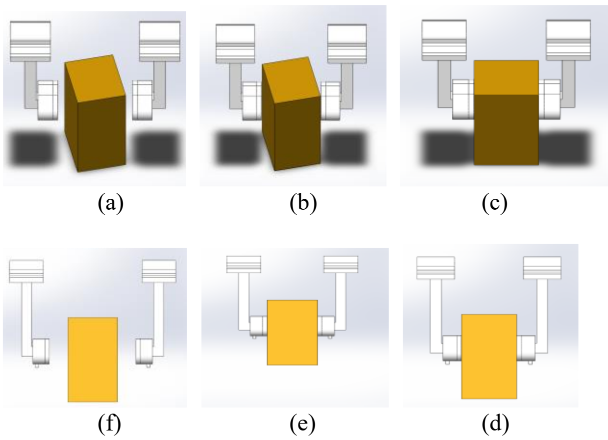

FIGURE 2: Grasping Phases.
(a) Approach (b) Make Contact (c) Align/Orient Object (d) Increase Grasping Force (e) Lift Provided by UAV (f) Release

3.3 Force Analysis

The end effectors apply a force normal to the walls of the package (F_{appl}) (see Fig. 3). Because of static Coulomb friction, the tangential force, F_t is proportional to the normal force,

$$F_t \leq \mu \, F_{appl} \tag{1}$$

where, μ is the static coefficient of friction.

The friction force, F_t , supports the weight of the package. Since the gripping system grasps the package from four sides,

$$F_t = \frac{W}{4} \tag{2}$$

where, W is the weight of the package.

The maximum weight that can be supported occurs when the package just starts to slip. Taking the inequality in equation (1) and eliminating the friction force yields,

$$F_{appl} = \frac{W}{4\mu} \tag{3}$$

If the package were grasped from two sides, then

$$F_{appl} = \frac{W}{2\mu} \tag{4}$$

If there were no limit on the magnitude of the applied force, then any package could be lifted; however, the corrugated cardboard walls are limited by the Edge Crush Test (ECT) value [29]. There are different maximum box weight guidelines for small parcel shipments [30] and palletized freight shipments [29]. For the purpose of validation of the proof-of-concept prototype presented below, either of these limits are significantly higher than operating conditions of the prototype.

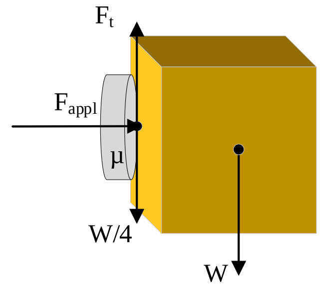

FIGURE 3: Force Relations (four-sided grasping)

3.4 Self-Locking

A lead screw is considered self-locking when the coefficient of friction between the nut and lead screw is greater than the tangent of its lead angle (λ), $\mu > \tan\lambda$. In the proof-of-concept prototype, a PVC lead screw is coupled with an Aluminum nut. The lead angle of this lead screw is $\lambda = 3.1°$, and $\tan\lambda = 0.054$. Since the coefficient of friction of PVC over aluminum is $\mu_{pvc/al} = 0.281$ [31], the screw is self-locking.

4. VALIDATION

Experimental validations were performed on the prototype shown in Fig. 4 and 5. Three experiments were conducted: package lifting, position misalignment, and orientation misalignment. The mechanism was turned slowly so that the effects of dynamic behavior would be minimized.

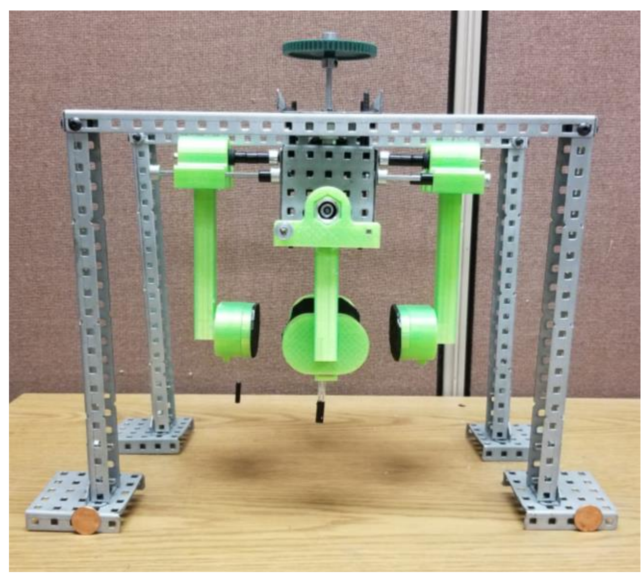

FIGURE 4: Experimental Prototype – Front View

A standard commercial 32 ECT off-the-shelf single wall corrugated box of size 10.16 cm x 10.16 cm x 10.16 cm (4" x 4" x 4") was used for the package lifting experiment. A custom size 3D printed box of size 7.94 cm x 7.94 cm x 13.02 cm (3.125" x 3.125" x 5.125") with corrugated cardboard affixed to the outside was used for the other two experiments. The smaller custom box was used in the pose misalignment experiments to increase the sensitivity due to the limited travel of the prototype.

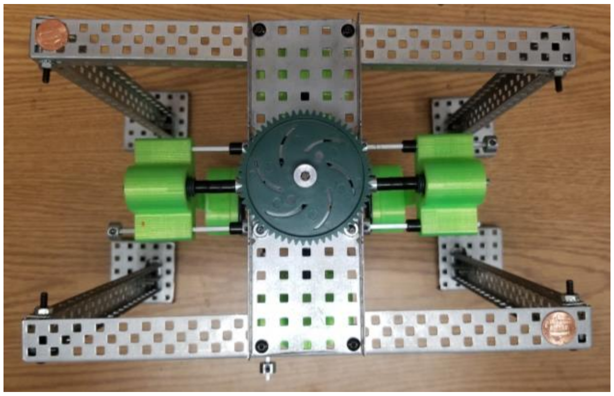

FIGURE 5: Experimental Prototype – Top View

A linear scale with 5 mm (x, y) graduations was used for the position misalignment experiment. A circular scale with 5° graduations was used for the orientation misalignment experiment. The origin of these scales coincided with the centroidal axis of the gear case on the prototype.

4.1 Package Lifting Experiment

This experiment determined the maximum weight that the prototype could lift. Success was defined when the package was lifted 150 mm from the tabletop, and no slip between the package and end effectors was observed.

Measurements of the applied force were made using a FlexiForce #A401 (piezoresistive) force sensor [32] installed in the end effector.

Initial tests of the mechanism resulted in a failure of the drive gear's square hole at 41 N. The gear was replaced, but the maximum total applied force was restricted to 33 ± 1 N for four-sided grasping and 15 ± 1 N for two-sided grasping.

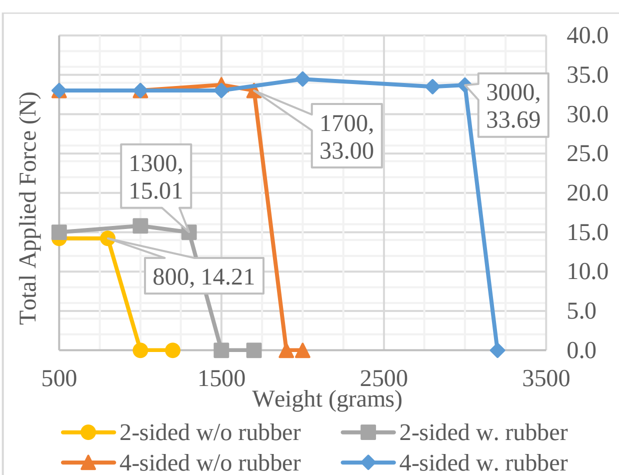

FIGURE 6: Weight Test Results

Calibrated weights were placed inside the box, and the grippers were actuated until the force sensor read 15 ± 1 N (two-sided grasping) or 33 ± 1 N (four-sided grasping). The prototype was lifted 150 mm in air to verify if the package would slip or not. At the weight where slip is first observed, the experiment was terminated.

Results of weight test experiment are presented in Fig. 6. The drops to zero indicate a failure in lifting the box at the respective applied force. The order of improving performance for the four cases – two-sided grasping (with and without rubber pads) and four-sided grasping (with and without rubber pads), is in accordance with the theoretical expectations.

A four-sided grasping approach allowed a heavier package to be lifted than two-sided grasping. The rubber pads allowed a heavier package to be lifted than the PLA end effectors.

4.2 Position Misalignment Experiment

A *grasp span* restricts the size of the boxes that a system can potentially grasp. A grasp span is essentially the vicinity inside which the grippers operate (see Fig. 7). Specifically, for four-sided grasping, it is the area generated by the endpoints of the four grippers while at their initial open position. Grasp span of this gripping system (see Table 1) ranges from 5.87 cm x 5.87 cm (2.3125" x 2.3125") (closed position) to 12.07 cm x 12.07 cm (4.75" x 4.75") (open position). This implies that the size of the box should lie between 5.87 cm < box size < 12.07 cm.

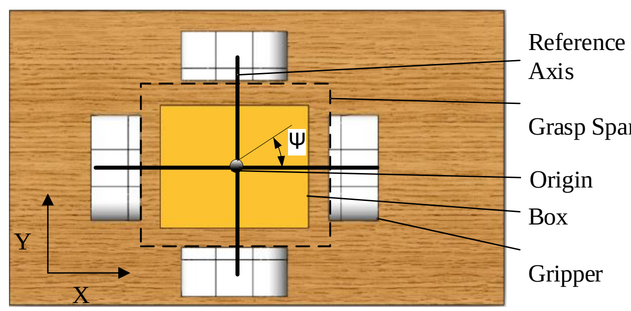

FIGURE 7: Grasp Span

In this experiment, the ability of the gripping system to push the package until all four end effectors are in contact is verified. Since the package is not lifted, no additional weight was included in the package. Success is defined when package center has been aligned with the gripping system to within 1 mm.

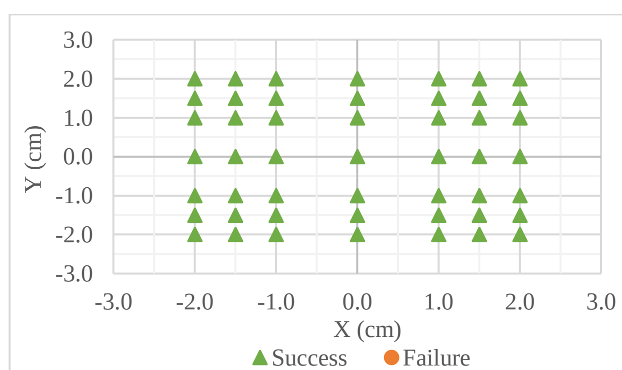

FIGURE 8: Position Error Success Chart

The package was initially positioned so that its center was aligned with a point on the table at a distance away from the gripping system center. The grippers were actuated until the package was contacted by at least one end effector. Actuation continued until the package's center stopped moving. If the package center aligned within 1 mm of the gripping system center, the grasp was considered successful. Otherwise, the grasp was considered to have failed. Results are shown in Fig. 8. Even though the gripping system was successful for all tests, a possible failure mode was identified, in which lateral friction between the end effector and the package could cause the package to jam between three of the end effectors (see Fig. 9).

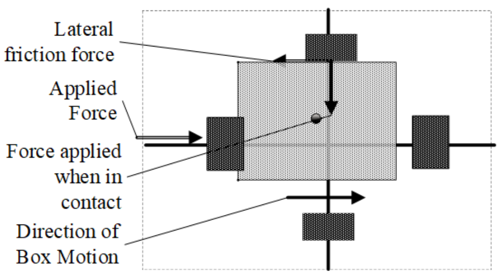

FIGURE 9: Effect of Lateral Friction Force

TABLE 1: Prototype Specifications

No.	Parameter	Value
1	Outer Frame Total (x, y, z)	40.5 cm x 22 cm x 27 cm
2	Outer Frame Internal end-to-end (x, y, z)	29 cm x 18 cm x 25.7 cm
3	Gear Case (x, y, z)	6.5 cm x 6.5 cm x 6.5 cm
4	Total Weight (including support frames)	1.8 kg
5	Weight of just Gear Case Outer Frame	0.2 kg
6	Net weight of all components in outer frame (excluding gear case)	0.92 kg
7	**Net weight of components transferable to UAV** (including gear case)	**0.88 kg**
7	Grasp Span (x, y) (open position)	12.07 cm x 12.07 cm (4.75" x 4.75")
8	Grasp Span (x, y) (closed position)	5.87 cm x 5.87 cm (2.3125" x 2.3125")
9	Major Axis Length of End Effector	5.715 cm (2.25")

4.3 Orientation Misalignment Experiment

In this experiment, the test package was centered in the grasp span but misaligned through an angle, Ψ, (see Fig. 7) relative to the gripper system coordinate system. Success was defined when the gripping system reorients the package so that Ψ is $0° \pm 1°$. Because of symmetry of the gripping system and the package, experiments were performed up to $\Psi = 90°$.

The grippers were actuated so that the box is contacted, and actuation continued until no further improvement in box orientation was observed.

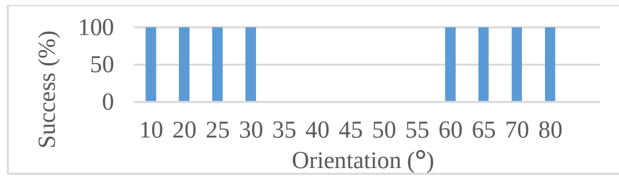

FIGURE 10: Orientation Error Success Chart

The gripping system successfully reoriented the package for misalignment below 30° (see Fig. 10). For misalignment between 30 – 60°, the gripping system would contact the package along its diagonal, which would prevent further improvements in orientation.

5. CONCLUSION

A gripping system for grasping corrugated boxes, which has the potential to be mounted on a UAV, was designed. The self-locking capability of the system was demonstrated under several package weights. The capability of the gripping system to automatically reorient misaligned packages was demonstrated. Two failure modes for grasping were identified, one for position misalignment and the other for orientation misalignment. These failure modes inform redesign to improve the gripping system.

6. FUTURE WORK

The next step in the development of this project is the construction of a full-scale prototype, which could be used to validate pose misalignment compensation on standard packages. Automatic handling of packages using a control system and integrating the force sensor is necessary before deployment on a drone. Design modifications to improve the performance of the system in the presence of the two failure modes are being considered.

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