Development of Dual-function Adaptive Landing Gear and Gripper for Unmanned Aerial Vehicles

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INTRODUCTION

Unmanned aerial vehicles (UAVs) have become increasingly popular in recent years due to their versatility in performing various tasks such as aerial photography, surveillance, and search and rescue. However, there is a growing demand for UAVs to operate in challenging environments with difficult terrains to take off or land on. Another challenge in UAV development is to improve their ability to interact with the environment by grasping, manipulating, and transporting various types of objects. This research aims to address these challenges by developing a lightweight dual-function adaptive landing gear and gripper prototype for multirotor aerial vehicles. The design can support UAVs to land on not only slanted surfaces but also moving platforms such as moving maritime vessels. When used as a gripper, the design allows UAVs to handle and manipulate a wide range of objects, securely carrying them for aerial delivery. To evaluate the functionality of the design, several prototype versions were developed and tested through a series of experiments. The results indicate that the innovative design not only enables dual functionality for adaptive landing gear and gripper, but also meets the requirements of being lightweight, modular, and easy to integrate into the UAV control system.

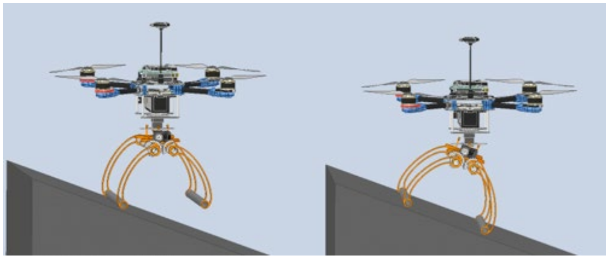

Figure. 1. Adaptive landing gear support UAV landing on slanted surface

MATERIALS AND METHODS

1. State of the art

Previous research has emphasized the difficulties for UAVs to operate in challenging terrains for takeoff and landing. Two main concerns for the control of the UAV during landing are the ground effect [1] and the dynamic roll over when landing on a slanted surface [2]. There are several research aim to solve these problems from the control side, such as [3] for the presence of ground effect and [4] using reverse thrust to improve landing performance on inclined surfaces. However, the results of landing performance in the mentioned research are mostly acquired in calm and controlled environment. Some other research tackle these issues with new landing gear design. The most common approach involves the use of active landing legs with complex control during landing [5], [6]. These legs typically have 1 or 2 degrees of freedom with control actuators, allowing the UAVs to adapt to the landing surface but also increasing the overall weight of the system. Another design approach for the landing gear employs a passive mechanism to adapt with the inclined surface such as in [7]. Recent research has focused on developing landing gears through mechanisms that mimic bird perching on branches [8] or through shape morphing [9]. However, these designs are complex, difficult to manufacture, and require specific landing situations and sophisticated control systems for perching.

Grasping and perching for UAV research normally group together because of their similarity in principle. A comprehensive review of the state-of-the-art in aerial grasping and perching can be found in [10]. There are two issues that must be addressed from the reviewed grippers: heavy weight not suitable for integrating on a small, lightweight UAV and requirement of complicated UAV control for grasping object. One of the simpler designs proposed was presented in [11], which attempts to combine grasping and perching with providing landing stability using two actuated 2DoF legs. However, the permitted landing slope was not discussed in the paper, and the design seems to only support a small landing slope.

The design introduced in this paper is aimed to tackle both landing on the slanted surface and grasping object without special, complicated UAV control algorithm while keeping the weight reasonable low, which will be suitable to be used in small and lightweight UAV.

2. System engineering process

Our design process adopts the system engineering methodology, commencing with defining the design objectives based on the comprehensive system requirements. These informative requirements were then decomposed into system design specifications and subsystem functional analysis and specifications. Multiple conceptual designs were generated and progressed into several versions of prototypes, which were evaluated through a series of experiments to determine their critical functional performance. Simultaneously, crucial components of the design were continuously enhanced. Ultimately, the best performed version of the prototypes was selected for integration with the UAV system.

3. System requirements

The first objective of our design is to create a landing gear that can facilitate landing on a moving vessel within the MarLand[1] project. The second objective is to integrate a grasping function that allows the UAV to securely lift and carry objects, as well as perch on different surfaces. A critical requirement for the system is that it should be lightweight and not interfere with the UAV's flight performance. Additionally, the design should be modular, enabling seamless integration between the landing, grasping, and perching functions. Furthermore, the design should be adaptable to function independently if required. After analyzing the overall requirements, a set of function-based requirement specifications was compiled as follows:

- Landing:
  - Capable of facilitating landing on a moving surface with slopes of up to 40º.
  - Support landing on a slanted surface without modification of the UAV control.
  - Must effectively reduce the landing impact and prevent the UAV from rolling over.
- Grasping and perching
  - Capable of securely grasping and carrying various objects.
  - Capable of securely perching on horizontal branches, walls, and surfaces without requiring specific adaptations to the UAV's flight control system.

The subject UAV for the design is commercially available Holybro X500 quadrotor kit[2].

4. Conceptual design

Following the functional analysis, a system concept was developed, shown in Figure 2. It comprises a landing gear, connected to the UAV through an articulated ball joint. The articulated ball joint allows the landing gear to rotate freely in roll and pitch with respect to the UAV during landing. It allows the landing gear to adapt to the slanted surface with slope up to 40º during landing. However, during flight and after landing, the ball joint must be locked in its position to prevent unwanted movement of the landing gear during the flight and take-off. A locking mechanism for the ball joint is required for these specific landing phases.

The landing gear has legs that serve the purpose of landing. These legs are designed to be actuated as a claw gripper with a single motor that opens and closes for both grasping and perching functions. This allows the UAV to pick up or perch on the object while hovering above it without special movement for grasping or perching from the UAV. In the absence of the grasping/perching function, the legs can be passive but still offer damping during landing with friction and elastic joints. The actuated legs also provide damping to help reduce impact during landing by controlling the opening of the claw when contact with the ground. On the other hand, if the grasping/perching function is required, a roller system will be provided between the two actuated legs. This system will assist in lifting the grasped object into an elastic net located between the legs. It also acts to prevent the rolling over of the UAV by creating a counter moment during the contact of the UAV with the ground. The elastic net acts as a cradle and will help securely hold the grasped object to reduce any interference caused by its movement during flight. The working concepts for landing on slanted surface; grasping object and reducing impact during landing are illustrated in Figure 3, 4 and 5 respectively.

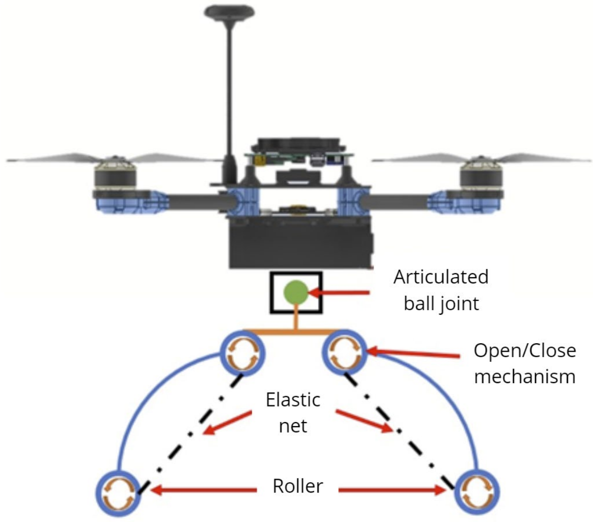

Figure. 2. Conceptual design with essential components

5. Component design and development

5.1. Design for rapid prototyping

For the proof-of-concept purpose, the development of designed components is done using accessible hobby grade parts and rapid prototyping methods. It allows faster and more affordable development and functionality testing and validation. Depending on the design and functional requirements of each component, two rapid prototyping methods can be selected:

- Fused Deposition Modeling (FDM) using UltiMaker S3[3] machine with PLA and PLA with carbon fiber reinforcement materials. This method is applied for rigid components such as mounting plate, socket, ball joint and legs.
- Stereolithography (SLA) using FormLabs Form 3+[4] machine with Flexible 80A and Elastic 50A materials. This method is applied for flexible and elastic components such as roller cover.

For some components with special engineering requirements such as roughness or smoothness for increasing or reducing friction, extra post-processing methods such as polishing or sanding are required.

[1] https://mecatron.rma.ac.be/index.php/projects/marland
[2] https://holybro.com/collections/x500-kits
[3] https://ultimaker.com/3d-printers/s-series/ultimaker-s3/
[4] https://formlabs.com/

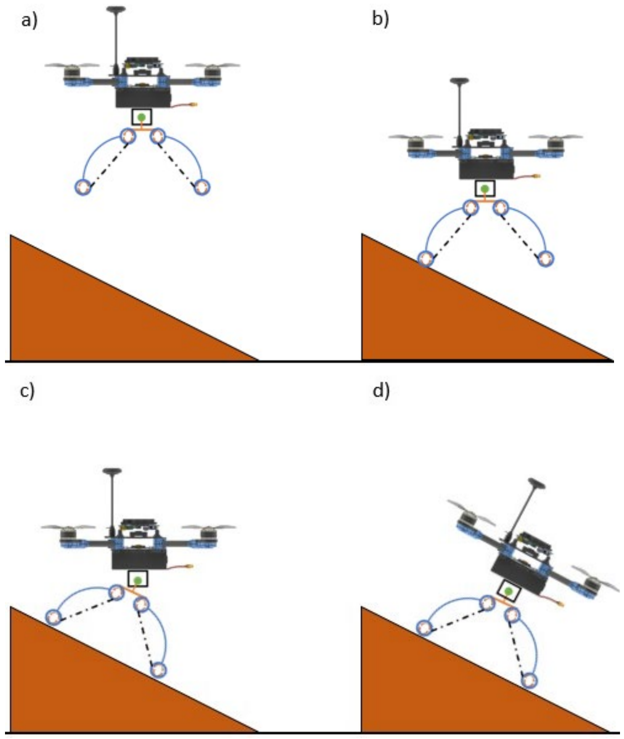

Figure. 3. Working concept for landing on a slanted surface: a). UAV prepares to land; b). one of the legs contacts with the surface, active roller is used to create counter moment to prevent the roll over; c). the articulated ball joint helps the landing gear to adapt with the slanted surface; d). UAV finishes landing, ball joint is back to locking position.

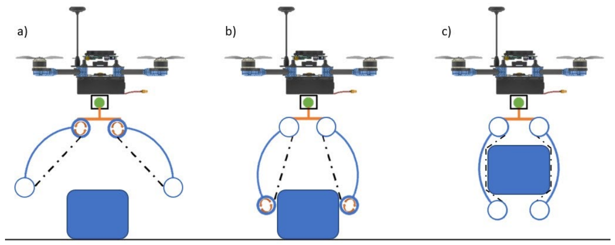

Figure. 4. Working concept for grasping object: a). UAV hovering above the target object, open the claw gripper, ready to grasp; b). claw gripper closes, roller lifts the object up; c). object is lifted into the elastic net.

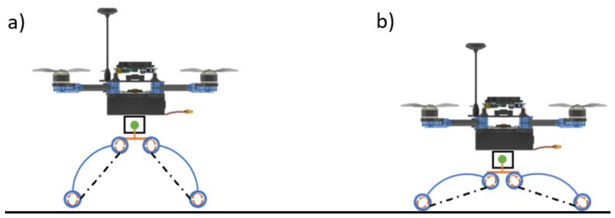

Figure. 5. Working concept for reducing impact: a). UAV starts landing, landing legs slightly close before ground contact; b). during ground contact, landing legs open to reduce the landing impact.

5.2. Articulated ball joint

The articulated ball joint is used to connect the UAV with the landing gear, allows the landing gear to rotate freely during the ground contact to adapt with the slanted landing surface with the slope up to 40^o, while it must be locked during flight and after landing. With that design requirements, the simple design of the ball joint is shown in Figure 6 with 3 different phases of flight. The ball joint consists of the upper socket part fixed to the bottom of the UAV, and lower ball stud fixed to the landing gear. During flight, because of landing gear's weight, and the friction between the lower part of the ball and the high friction surface bearing of the lower part of the socket, the landing gear will be restricted in movement. During touch down, the landing gear contacts with the ground, the ball stud moves up inside the socket and can rotate freely up to 40^o, it allows the landing gear to adapt with the slanted surface. When the UAV fully lands, the ball stud moves up till the end of the socket, with special design of the upper part of the ball and the socket end, the ball joint will be locked in its position for the next fly.

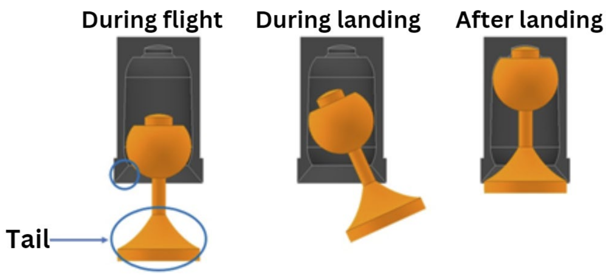

Figure. 6. Ball joint in different phases of flight

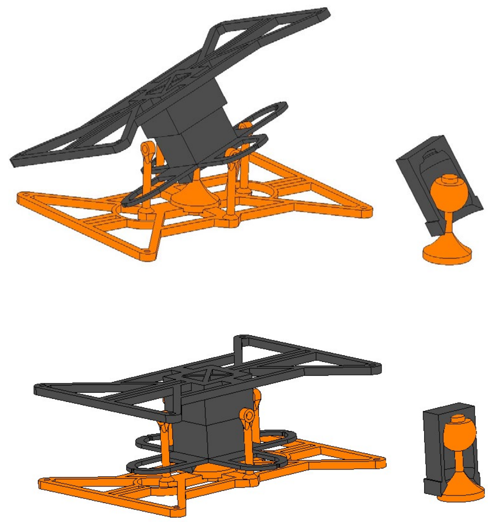

Figure. 7. Assembled ball joint during landing: freely rotating joint (upper) and after landing: ball joint in locking position

Figure 8 represents the assembly parts of the articulated ball joint. The bottom frame includes the ball stud, mounting plate with the landing gear and 4 vertical bars used to limit yaw movement. The socket is assembled from 2 halves and connects with the top mount plate.

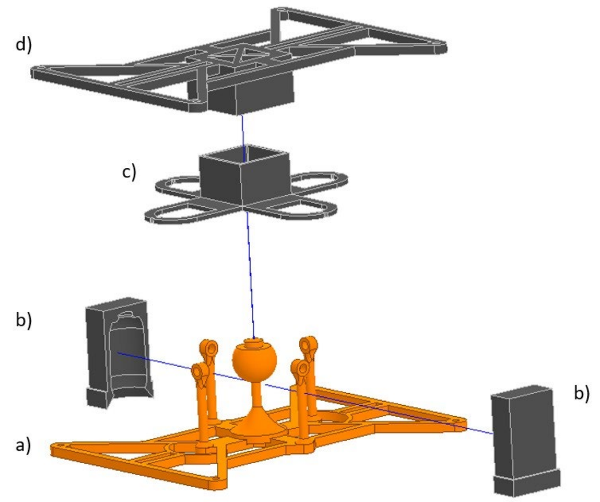

Figure. 8. Ball joint parts presentation: a). The bottom frame fixed to the landing gear; b). 2 halves of the ball joints socket; c). Cover of the socket for assembly and anchor points for limiting the yaw movement of the bottom frame; d). Top mount frame fixed to the UAV bottom.

5.3. Claw gripper

The claw gripper consists of bottom frame from the ball joint carrying one Dynamixel X430-W350-R motor for opening and closing the two claws. Each claw has 2 legs to hold the roller at the other end of them. Figure 9 shows the claw gripper in opening and closing position. If the grasping function is not required, to support only landing, there is a passive damping option. It replaces the active motor to open the two claws with elastic bands and uses it to provide damping during landing. This design saves a lot of weight from the landing gear.

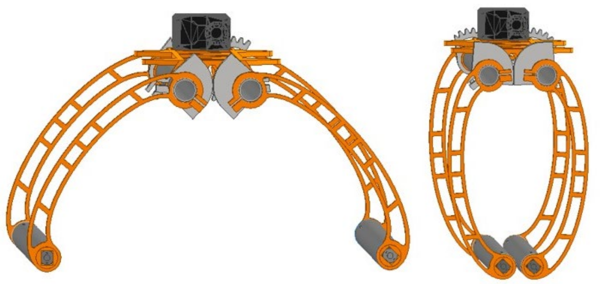

Figure. 9. Claw gripper in opening and closing position.

To reduce the ground effect during landing, the length of the leg is chosen so that the ground clearance of the rotor from the required opening position for landing of the two claws is higher than the rotor radius [1]. The required opening position for landing is defined when the distance between two rollers is equal to the distance between the two rotors. Furthermore, the legs must withstand the landing impact, the closing force, and the weight of the carrying object, while they must be kept light weight. Therefore, the design of the legs has been optimized between the strength and weight. Figures 10 and 11 show the measurement setup and result for elastic modulus estimation of the leg material using the first design. This result is used in Finite Element Analyses calculation for the design of the legs with multiple linking bars between two main bars. The linking bars which show neglectable stress applied to them will be removed. The design optimized process and the final design of the leg are shown in Figure 12.

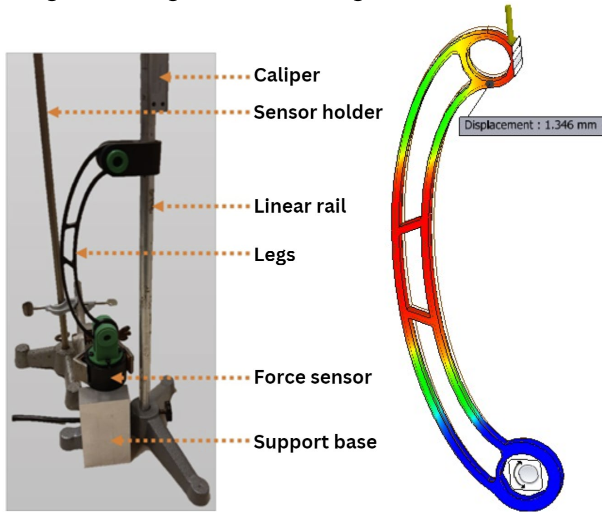

Figure. 10. Measurement setup for elastic modulus estimation for the leg (left) and FEA calculation of displacement for similar applied force (right)

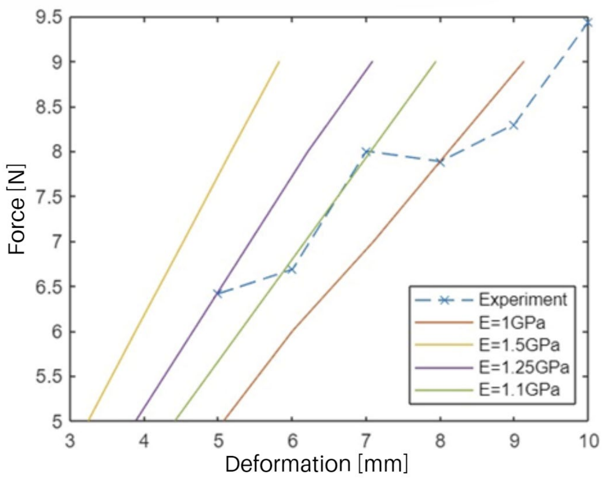

Figure. 11. Result of the elastic modulus estimation for the leg material by comparing the real measurement from the experiments and the FEA calculation with different elastic modulus.

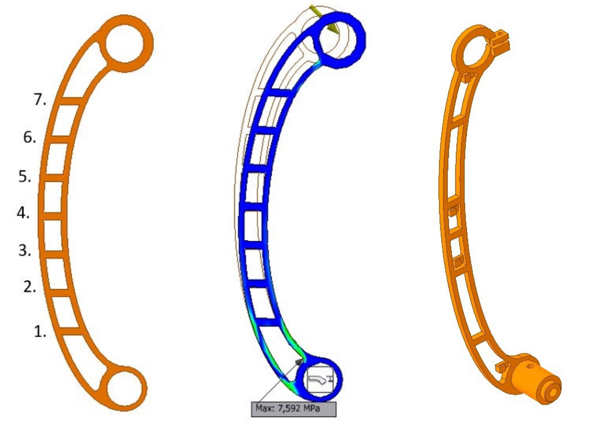

Figure. 12. Leg design optimizing process using FEA calculation (left and middle) and the final design result (right).

5.4. Roller

The roller's objective is to lift the grasped object up into the elastic net. The pressure on the grasped object is provided by the Dynamixel X430-W350-R motor. The roller must provide sufficient friction and moment to lift the object up. Figure 13 represents the assembly parts of roller. The motor used to actuate the roller is small motor Joy-it Com-Motor03[5]. The carbon tube is used to reduce the weight of the roller. The roller cover provides the grip between the object and the roller, it is 3D resin printed using flexible material, the outer surface of the cover is designed to be rough to increase friction. The diameter of the roller is calculated to be 12mm so that it can lift 500g objects.

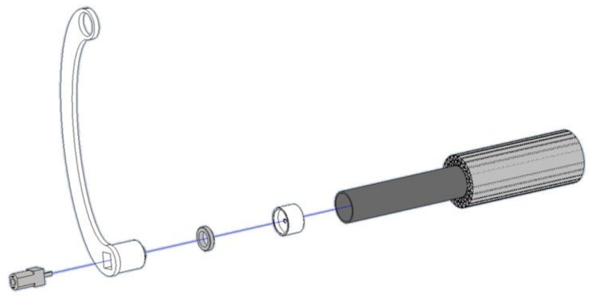

Figure. 13. The assembly parts of the roller. From left to right: roller motor, leg with motor holder, bearing, adaptation for the carbon tube, carbon tube, roller cover.

RESULTS

Multiple versions of the device are developed. Figure 14 presents one version used for both landing and grasping and uses an active motor to open the 2 claws. By customizing with options such as: fully functional landing gear/ grippers or only for one specific function; using active or passive damping during landing, the components of each version can be changed, removed to the specific requirements. The lightest version, only used for landing, weighing less than 200 grams, includes an articulated ball joint and four legs with passive damping, which is comparable to the standard landing legs of the X500. In contrast, the full version, which features an active grasping motor and roller, weighs approximately 400 grams.

To determine their key functional performance, a series of experiments were conducted. Critical aspects such as weight, grasping capability, and the device's ability to land on a slanted surface were analyzed.

To analyze the grasping capability of the claw gripper, a measurement setup was constructed to test the grasping with different weights and sizes of the grasping object – which is shown in Figure 15. The testing objects are different empty boxes with 4 different sizes, to which weight is added till the gripper starts to fail to lift the object. The same pad is used for the contact surface between the box and the roller to achieve the same friction throughout the test.

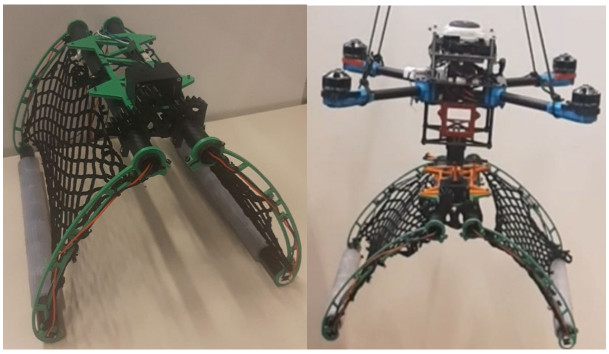

Figure. 14. Fully functional version used for both landing and grasping, with active damping from an active motor: standalone (left) and mounted under the X500 quadrotor

The result of the test is shown in Figure 16. It shows that the optimal size of the object for the gripper is around 150mm. For that size, it can grasp object up to 800g. To achieve the 500g weight specification for the grasped object, the size of the object must be smaller than 220mm.

Figure 17 is a combination of grasping experiments with different real-life objects, it shows that the roller can handle various sizes, shapes, weight, and surface frictions.

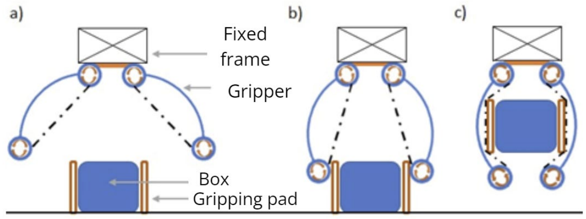

Figure. 15. Measurement setup for grasping experiments: a). gripper is mounted on a fixed frame, open and ready to grasp the tested object; b). two claws close on the tested object; c). roller lifts the object up – grasping success – test will be repeated with added weight to the tested object.

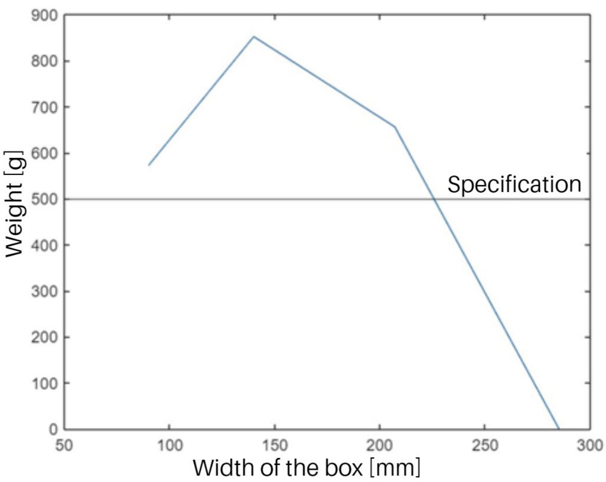

Figure. 16. Grasping capability of the gripper with limit for weight and width of the object box

[5] https://joy-it.net/en/products/COM-Motor03

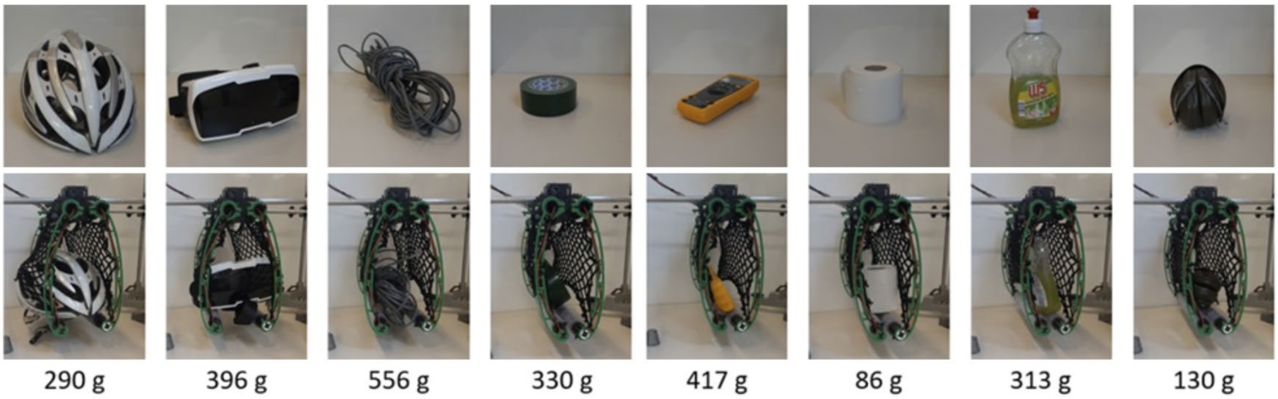

Figure. 17. Grasping test with different real-life objects

To analyze the ability to adapt with slanted surface during landing, a test setup is constructed to control the descending speed and achieve different landing orientation of the quadrotor. It consists of a surface for landing which can be adjusted in slope angles, a pulley system to mount the quadrotor, allows it to descent with certain speed, and a camera for recording the scenario. The setup is presented in Figure 18. The result shows that with our landing gear, the UAV can successfully land on a slope of up to 40°, with different descending speed and landing orientation.

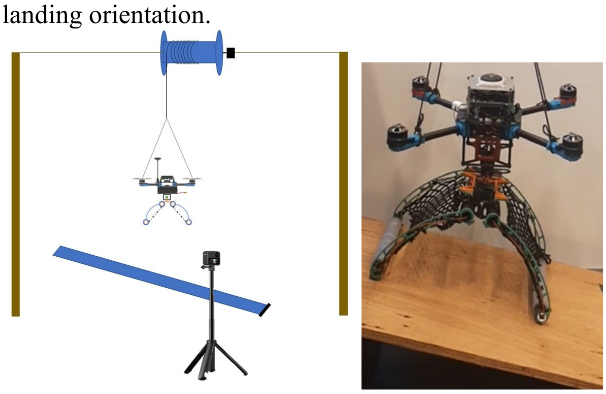

Figure. 18. Slanted surface landing test set-up and result

CONCLUSION AND DISCUSSION

The paper introduces a novel design of dual-function adaptive landing gear and gripper for multirotor aerial vehicles. The results demonstrate that the new device enhances the versatility and functionality of UAVs, enabling them to operate in challenging environments such as landing on a slanted surface or perching on horizontal branch or wall; and to perform complex missions required interacting with the environment through transporting object using two claws active gripper. The proposed design and developed prototype meet our requirements of landing on slope up to 40°, and able to carry various objects up to 500g while being light weight. Moreover, with our design, the UAV is able to do such tasks without any specific adaptations. Future work will focus on integrating the landing gear and gripper with the UAV control system and optimizing the design further for better performance.

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