Iterative development of a mechanical gripping system for civil counter-UAS applications

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Abstract— **In recent years, drones have become widely used. Consequently, their potential to cause harm or damage to people, property, or infrastructure has also increased. As drones have become more prevalent, so has the need to counter them and prevent potential misuse. Unlike net or projectile-based systems, a gripper enables precise midair capture and secure handling of the intruder drone without causing uncontrolled descent or collateral damage. This paper presents our iterative development process for such a mechanical gripping system for use in civil counter-UAS applications. After a brief overview of existing gripping systems, we will describe the initial development steps and progress to increasingly complex design solutions. During the development process, three prototype designs were built and evaluated, one after another. Finally, we present our final design, which satisfies all requirements for integration into the UAS and can be used to catch the intruders in mid-flight.**

NOMENCLATURE

CAD	Computer Aided Design
CFRP	Carbon Fiber-Reinforced Polymers
FEM	Finite Element Method
PLA	Polylactic Acid
PSSB	Pre-Stressed Spring Steel Band
PWM	Pulse Width Modulation
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle

I. INTRODUCTION

Drones have become powerful tools across various industries, from aerial photography and agriculture to logistics and disaster management. However, their growing proliferation also increases the risk of misuse. Unmanned Aerial Vehicles (UAVs) can threaten national security, public safety, and critical infrastructure when operated irresponsibly or with malicious intent. This has led to the emergence of Drone Defense, a field dedicated to detecting, mitigating, and neutralizing rogue drones to ensure safe and secure airspace. UAVs weighing up to 25 kg can easily be operated by hobbyists, increasing the risk of accidental or intentional intrusion into restricted areas, such as airports, event venues, and military sites. To prevent unauthorized entry into such no-fly zones, drone defense measures can be implemented. One focus of mitigation is the capture and removal of intruder drones. Existing systems use drag nets or nets that are fired to catch and remove the intruder drone. This paper outlines the iterative development of a gripping system mounted on a counter-drone that can capture and physically move small multicopters.

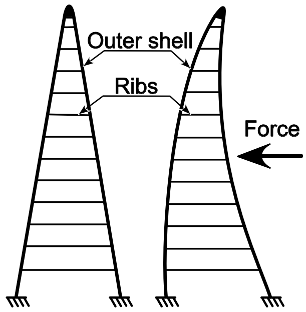

Fig. 1. The simple Fin Ray® geometry. When force is applied to one side, the geometry bends around it.

II. RELATED WORK

A wide variety of methods for gripping different objects have been published in the literature. The main areas of research application include gripping high-voltage cables [1], hazardous [2] or explosive [3] materials, and pipes [4], [5], [6]. Gripping systems are also available for unmanned underwater vehicles [7]. Some gripping systems on UAV are often implemented in combination with a robotic arm [8].

Gripping systems based on the Fin Ray® Effect[1] are mainly found in robotics [9]. This type of manipulator was created by Festo and inspired by fish fins. The basic idea is that fish fins are arranged in a V-shape, with connective tissue in between them (see Figure 1). Pulling or pushing one side of the V causes the fin to deform into a crescent shape [10].

These are used as ”soft robots”. Soft robots have a continuously deformable structure with muscle-like actuation that emulates biological systems, resulting in a relatively large number of degrees of freedom compared to hard-bodied robots in areas where flexible access is required [11]. In some cases, gripping technology based on this effect can also be found in grippers attached to drones, where it is mainly used to grip small, irregularly shaped objects([12], [13], [14], [15], [16]).

Researchers from Colorado State University [17] developed a very interesting gripping approach where the basic design includes Pre-Stressed Spring Steel Band (PSSB) to grasp different objects. The designed gripper can quickly close and re-open mechanically, and has the capacity to carry loads of about 2,3 kg. However, the gripper is small (with an arm length of about 30 cm), and it is unclear how well it can be scaled and adapted to capture small UAVs.

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[1] Fin Ray® is a trademark of EvoLogics GmbH, Berlin, Germany

TABLE I

GENERAL COMPARISON OF KINETIC DRONE CAPTURE METHODS: GRIPPER VS. NET GUN.

Category	**Gripper Systems**	**Net Gun Systems**
Engagement Method	Requires the interceptor drone to physically contact the target with a claw or robotic arm	Fires a net projectile at the target from a short distance (typically 3–15 m) [24]
Reload Capability	If the capture maneuver fails, the gripper can be recharged for a new attempt	Single-use per shot
Precision Requirement	High precision & control during interception [25]	Medium precision; relies on projectile accuracy [26]
Impact on Target	Low to medium: The gripper is typically designed to minimize damage, but if the target is fragile crushing or breaking parts is possible	Low- if the net is connected to the carrier drone; High- if the net has no connection to the carrier drone
Target Size/Shape	Highly specific	Highly versatile
Mechanical Complexity	High	Low
Deployment Range	Limited by manipulator reach and flight precision	Can engage from a greater distance depending on net propulsion [27]
Dependency on Weather	Low: Flight limitations are set by the carrier drone	High: Nets can be highly sensitive to wind and adverse weather conditions [28]
Cost per Operation	Higher initial cost, but low operational cost	Lower initial cost, higher per-use cost (due to consumables)
Integration Complexity	High: Requires an enhanced environmental perception system, as well as advanced control algorithms for interception manoeuvres	Low: Simple integration with existing drone or launcher systems
Overall Advantages	Precise, reusable, safe, and enables intact drone recovery	Simple, quick, low complexity, and effective in open environments
Overall Disadvantages	Complex, heavier, slower, and higher energy consumption	Less controlled outcomes, single-use, potential collateral damage

The rise of drone defense startups reflects growing demand for affordable and scalable counter-UAV technologies. The DroGone [18] startup from Switzerland has developed an automatic drone with a static net on top to intercept drones in mid-flight and bring them down. The US-based company Robotican uses a drag net underneath the UAV to capture the intruder drones [19]. Typical systems on the market for drone defense are based on net cannons. The cannon shoots out a net at the target drone, catches it, and flies away with it. Such companies like Fortem Technologies (US) [20], Airspace Systems (US) [21], Argus Interception (GER) [22], as well as Delft Dynamics (NL) [23] All these companies already brought their counter-UAS products to market.

Although net cannon systems are practical and inexpensive, they have a number of disadvantages. These include a limited number of shots, an unreliable hit rate, dependence on the weather, and possible collateral damage to the ground. In contrast, the gripping system is reusable, operates precisely, and is more independent of weather conditions. The operational trade-offs between the two methods are summarized in Table I. However, due to the variety of commercial net gun systems available on the market, we decided to develop and test our own gripping system for counter-drone activities.

III. DEVELOPING OF THE GRIPPING SYSTEM

The goal was to build a lightweight gripping system that could securely hold the drone in the air while remaining resilient and agile. The intruder drone was defined as a DJI Phantom 1[2]- class drone weighing 1,5 kg with an average diameter of 400 mm. Due to limitations set by the carrier drone, the first iteration of the gripping system should not exceed 4 kg. Ideally, the weight will be minimized in future iterations and will not exceed 2 kg.

The initial design was inspired by a plant *Drosera glanduligera*, which belongs to the carnivorous plant family and can be found in regions of South Australia [29]. The plant uses two main catching principles to capture prey. Firstly, it has adhesive glue drops that do not let the prey escape, and secondly, it has tentacles (usually glue-free) that snap the prey into the center. Although the plant's closing mechanism has a hydraulic origin, the overall design of gripping system was inspired by its tentacles.

A. Pre-development steps

The simple design was implemented to gain experience in this field. It consisted of four metal rods (three inner and one outer) and a mechanical servo motor as the actuator (see Figure 2). The servo motor's rotation motion is translated into forward motion. The top rod is connected to the motor, and the other three rods are fixed to the bottom. All rods are connected at the top. When the top rod is pushed out, the entire structure bends. In order to translate the motion to the bottom rods and not just deform the top rod, the connectors need to be placed alongside each other.

The main problem with that design is that a large amount of force is required for the system to close, and the force

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[2] https://www.dji.com.cach3.com/pr/product/phantom/index.html

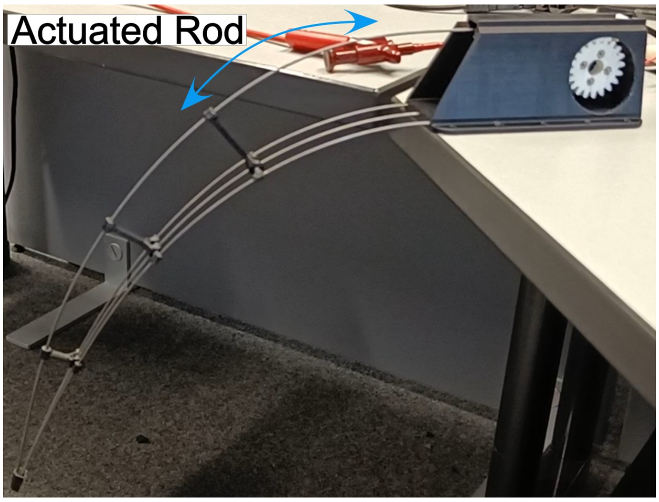

Fig. 2. First design of the arm.

is greatest when the tentacle is in its closed position. Due to the leverage, a small force applied to the tip causes the entire tentacle to become unstable. Measurements show that the first structural instability occurs when a force of between 4 and 10 N is applied to the tip of the arm. This was difficult to measure, however, because the structure (rods) bend inward. The minimum force (along the rods) required to cause the back rod to buckle is 4,8 N. This measurement was taken with a force gauge, and only the maximum force was recorded. This suggests that the design of the structure sets the limits, because of instability (bending to the side), and not critical stress in the material. Such design has its fixed end position, and applying extra force from the motor to top rod will result in the rod being deformed, rather than the system closing. The main advantages of such a solution are simplicity and light weight.

B. *Refining of the design with rods*

To solve the stability issue, an additional rod was added to the back for stabilization. The number of rods on the back was increased by two to increase the area moment of inertia, thereby increasing the lateral-stability. When a force is applied to the top, in the direction of the rods, the bulk remains between the joints. Despite that, the system's stability has been significantly improved, and the issue of bending to the side has been resolved.

C. *Implementation of plate as inner arm structure element*

The next step in the development process was to replace the rod construction with a lighter and potentially stiffer material. The idea was to evenly ”distribute” the rods over a surface and see the results. The plate was chosen as a suitable replacement for the metal inner rods. Three types of materials were tested. Figure 3 shows the different materials built into the arm and loaded with a small force applied to the tip. The rods and plates are connected by rigid ribs. Interestingly, the end-point position was reached by all materials identical (or nearly identical) to the rod design. The behavior under axial load was similar for the carbon and glass fiber plates. Their performance under side loads was slightly worse, but still acceptable. The aluminum plate deformed much more than the others. This can be traced back to the plate's low thickness. The goal of the test was to see how the arm would perform if the stabilizers were replaced with a plate on the inside. The test results clearly show that the back rods are buckling the most between the mounting plate and the first rib. In fact, the tension within the rods is causing plastic deformation. This can clearly be seen after disassembling the test bench.

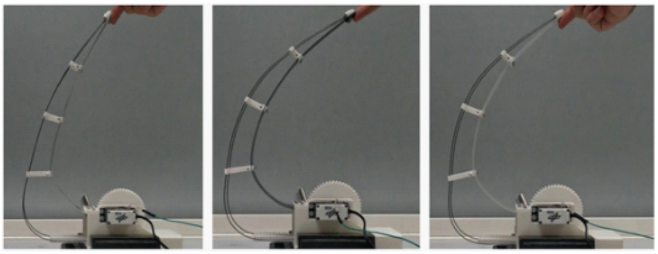

Fig. 3. Static test. From left to right: Aluminum plate (0,3 mm); Carbon plate (0,5 mm); Fiberglass plate (0,5 mm).

In summary, stabs offer better performance under side forces, but they are more challenging to mount and require installation on the underside to match the stability of a plate. In contrast, plate mounting is simpler and more rigid, with an easy assembly and straightforward design; however, it performs poorly under side forces. The choice between the two depends on whether side-force resilience or ease of mounting and simplicity is prioritized.

D. *First Fin Ray® prototype*

Based on the findings from the previous step, a new design was specified. The goal was to simplify the mounting procedure. That is why carbon plates were chosen over rods; the plates are easier to assemble than the rods. Additionally, the carbon plates are more flexible than metal rods, which should solve the problem of plastic deformation. Another main design change was swapping the ”push” configuration for a ”pull” configuration. Instead of pushing out the back plate, the new design retracts the inner plate, which automatically eliminates the buckling problem with the back plate. The schematic of the motion is shown in Figure 4.

As the inner plate is now pulled inwards, the housing, which holds both plates, sets the limits. Rather than using rigid connectors, which maintain a constant distance between the plates, flexible connectors were chosen. This would minimize the distance between the plates in the open state and allow automatic adjustments to the space between the plates in the closed state. The connectors can be made from a flexible material, or the joints (hinges) can be designed into them. For practical reasons, the second approach was preferred. The connectors now have two joints, located as close as possible to the plates. Each joint has a different step length (the distance between the back plate and the inner plate), causing the arm to converge into a crescent shape. The

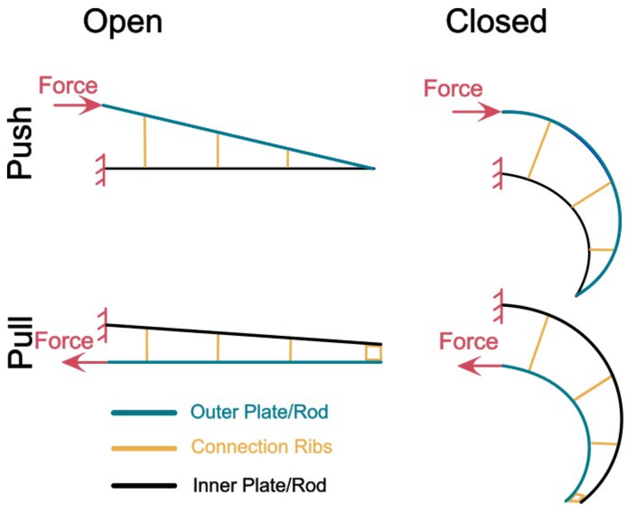

Fig. 4. "Push" and "pull" configurations in opened/closed states.

step size, the length of the hinges and the housing dimensions were empirically defined during laboratory testing. The outer and inner plates are the same size. The early CAD design of the plates with hinges can be seen in Figure 5.

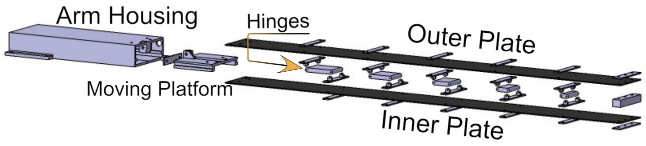

Fig. 5. Exploded-CAD drawing of plates with the hinges in between.

E. Mechanical actuation design

Shortly after the primary design of the arms was finalized, the development of the activation mechanism was initiated. The main idea was to minimize the number of required actuators and activate the gripping system with a simple, robust mechanical principle. With this idea in mind, the first concept was developed. It was based on a constant force spring. Due to the possibility of blocking a single arm during mid-flight capture, it was decided that each arm would have its own spring for closing. This would ensure that the other arms would close independently. Another benefit of this design is that, since each arm is activated by its own spring, the spring force is much smaller than if one spring were to activate all of the arms. This should lead to smaller, lighter springs. Laboratory experiments determined the minimum force needed for each arm to be ~73 N.

The gripping system was designed to have only two states: open and closed. All moving elements, such as arms, springs, and the dog box (which will be explained in the next paragraph), are connected by cords. In the open state, all of the springs in the gripping system are preloaded and locked. This is done with an electric motor. As soon as the spring is stretched, the outer plate detents and rolls back, and the plates in the arm return to their initial position due to Hooke's Law. When the dog box releases the spring, it pulls the inner plate down, causing the arm to move into the closed position. This is the basic mechanics of the gripping system (see Figure 6).

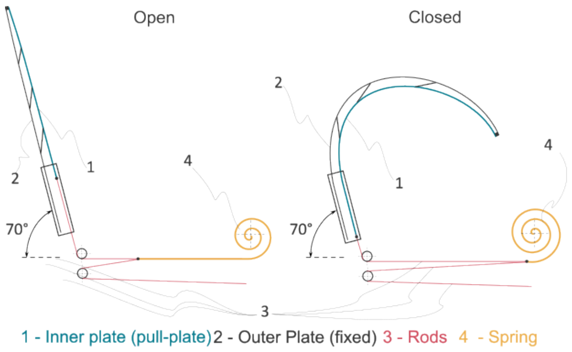

Fig. 6. Schematics of the "open" and "closed" gripper arm states with help of constant force spring.

The mechanical release system also underwent an iteration process, but the basic principle always remained the same. An important design element of the release mechanism is the ability to release and tension the springs by coupling it with an electric motor. This is where the dog box was designed. It works as a clutch between the shaft and the electric motor. It has four pins that can be rolled in or out to connect or disconnect the motor-spring-arm connection. The name is derived from the auto-moto scene, where race car gearboxes without a synchronizer are called this way. The connection from the dog box to the arm is made with cords and a pulley system.

Since all of the design solutions for the mechanical parts had been finalized in the conceptual phase, the first CAD design could be created. Later, the prototype was built. Figure 7 on the left shows the CAD isometric projection of the gripping device, and on the right, assembled prototype. Under the green gear wheel (in CAD drawing on the left) in the middle is the dog box and connection shaft. This is a six-arm gripping system. The number of arms was chosen to correspond with the number of arms on a hex copter. This should simplify mounting problems between the gripping system and the carrier platform.

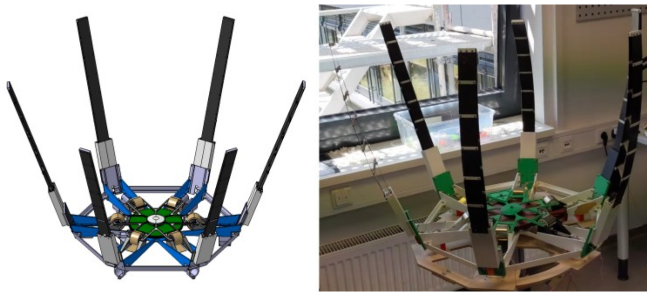

Fig. 7. Left: Isometric projection of gripping system in CAD; Right: First assembled prototype.

Figure 7 illustrates the gripping system in its open state with the angle between the arms and the base plate of 70°. This was an intentional design choice. During early tests, it became clear that it was impossible to achieve a 180° closing angle with this design of arms. The design with a 70° angle was a compromise, with the goal to test whether the implemented design solutions and gripping system were functioning properly.

As mentioned earlier, the electric motor was chosen to pretension all of the springs in the mechanism. For a number of practical reasons, a high-torque servo motor was selected for this purpose. Unfortunately, the motor was not strong enough to pull all six springs by itself. Therefore, a gear was designed to provide enough torque for the opening sequence.

After building the prototype and starting to test it, some initial problems were discovered. For example, the cords connecting the shaft and plates jumped out of their ducts, and the 3D-printed gears were not well aligned, especially under load. During this period, the need for a ratchet mechanism was also detected, because the servo motor had difficulty holding all the springs under tension. This would allow the main motor to be powered off when the gripper has reached its open state.

After the major teething problems were eliminated, the gripping system of the proof-of-concept demonstrator was operational. The system was functioning at a basic level. The closing time was measured to be less than one second. Because the arms and spring are flexible, the gripper shook for a moment after closing. This was not considered a critical issue neither for gripper structure nor for drone because the arms are lightweight, and the excitation of the gripper was stochastic, separate for each arm, and had a short-term character.

Since the concept was functional, the decision was made to extend the basic design. In its original form, the gripping system produced significant aerodynamic drag on the top of the drone. The main focus was therefore to ”open” the gripping system to reduce air resistance and provide a larger surface area for catching the intruder drone. The solution was to integrate a joint into each arm. The rotation axis was placed on the bottom of the main body, and the housing-box design was improved with an extra leverage point. The spring is now indirectly connected to the rotation shaft. You can see the schematics of that connection in closed and open positions in Figure 8. This design was realized in the prototype gripping system, which can be seen in Figure 9.

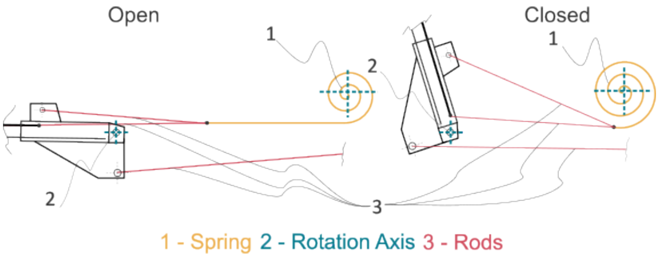

Fig. 8. Schematic of the ”180°-open” and ”closed” gripper states with help of constant force spring.

After the practical implementation of the design and laboratory tests, we could see that the basic design idea was functioning. Unfortunately, the gripping system does not open fully, to 180°. This is due to the different rope lengths connecting the various points, which requires fine-tuning of the system's nodes. This issue was not resolved in this prototype.

The developed prototype is an interesting proof of concept, but it is not practical to use it as a gripping system on top of the drone. Despite its good closing time of 0,5 seconds, self-reopening capability, and fully mechanical release mechanism, the system's total weight of 4,2 kg exceeds the drone's payload capacity. Therefore, based on the experience gained, the system needs to be redesigned to be lightweight enough for mid-flight interception.

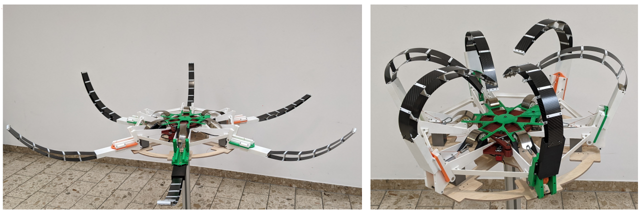

Fig. 9. Working prototype of the gripping system with a 180° opening angle. Left: open state; Right: closed state.

F. Gripper with servo motors

First approximation calculations were made to determine if the weight of the gripping system could be significantly reduced by using lightweight materials instead of PLA. We assumed that the main frame of the gripping system is made from carbon fiber materials and the critical joints are made from lightweight aluminium, without the mechanics in the middle and no arms. In that case, the gripper frame alone would weigh about 0,69 kg. For comparison, PLA frame weighs about 0,73 kg (the estimated CAD model excludes fasteners). Upon comparing the materials, we can conclude that the aluminum and Carbon Fiber-Reinforced Polymers (CFRP) are stiffer and more rigid than the PLA. We can presume that this material could absorb mechanical shocks more effectively from catching intruder drone, even without Finite Element Method (FEM) simulation. However, the weight of the frame remains significant.

All major components were weighed and the mass budget of the gripping system, including all three versions of it, is presented in Table II. Even without the springs, the remaining weight of last PLA-prototype is about 3 kg, which still does not fully satisfy the mass requirements.

The general design idea for the next iteration was to use an electric servo motor for each arm and eliminate the frame by integrating the gripping system with the drone. In that case, the drone's carbon frame should also act as the gripping system's frame. One of the major requirements for the mechanism is to lock the arms in place. This was done to prevent the servomotor from constantly being under load tension, as it was in the previous design.

Figure 10 (left) shows the CAD design with the servo motor, which has a moving arm that can ride along the slot

TABLE II

THE MASS BUDGET OF THE ASSEMBLED PROTOTYPE AND ITS ROUGH ESTIMATION FOR CARBON AND ALUMINUM MATERIALS.

Component	**First Prototype [kg]**	**180°-Prototype [kg]**	**6 Servo-Arms (equivalent) [kg]**
Gripper Frame	0,73	0,73	∅
Dog box & Gears	0,33	0,33	∅
Arm Holder (6x)	∅	0,42	∅
Spring (6x)	1,20	1,20	∅
Arm (6x)	0,63	0,63	1,40
Diverse (servos, fasteners, connector parts, ect.)	0,85	0,90	0,92
∑ Total Weight	3,74	4,20	2,32
Relative Comparison	100%	112%	62%

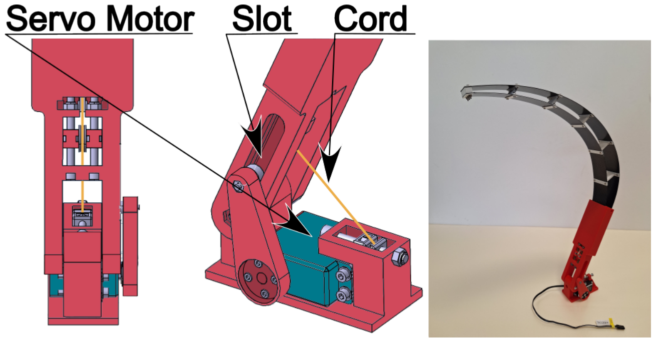

Fig. 10. The final arm design features an integrated servo motor. Left: CAD design. Right: Assembled arm.

and lock. The inner plate is connected to the base plate, with the motor over the cord. Now, the servo motor pushes the whole cell up, pulling the inner plate into a crescent shape. To allow for adjustment, the pulley is mounted on two screws that enable it to move. This ensures the arm will fully close and guarantees multiple arms can be adjusted to have the same closed position. Adjusting the pulley's position using the screws changes the distance between the pulley and the arm's center of rotation, thus setting an equal contraction amount for all arms. Additionally, the bottom mounting point for the cord is variable, allowing the pretension to be set precisely. This mitigates the effects of manufacturing tolerances and any slight wear or stretch of the cord. One arm was 3D printed and analyzed in Figure 10 on the right. The new assembled arm weighed 0,39 kg, and the estimated weight of the gripper with six arms would be 2,32 kg (see Table II, third column). This design decision was considered promising. After resolving all the initial design issues, the gripping system consisting of four[3] arms was assembled and tested.

Using four arms instead of the designed six resulted in a significant gap between the arms, allowing the captured drone to fall out. The simplest solution was to stretch a net between the arms. Figure 11 shows the complete gripping system in open and closed states, mounted on a wooden plate inside the lab.

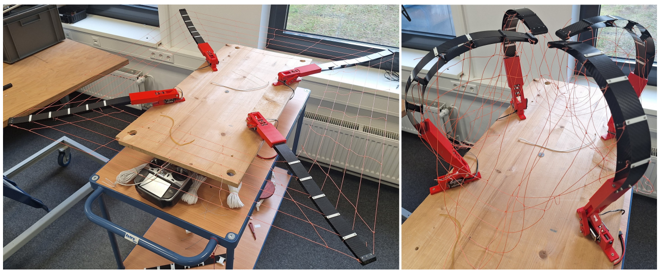

Fig. 11. The four-arm assembly on the wooden plate with the net in between. Left: open state; Right: closed state.

The final gripping system has an arm length of 0,64 cm. In combination with three additional arms, the estimated volume in the closed state is 0,45 m^3. The complete, four-arm gripping system weighs 1,90 kg (including electronics) in its final configuration and closes in less than 0,3 seconds.

Its design fully meets the requirements for integration onto of the multicopter. The servo motors can easily be controlled with a standard Pulse Width Modulation (PWM) signal for the opening and closing procedures. Additional electronics could also be integrated to monitor the state of the servos and, therefore, the gripper.

IV. THE FIRST FLIGHT TEST

The first test flights were conducted in early 2025. One of the objectives was to evaluate the interaction between the grappling system and the drone during flight. The second objective was to perform a capture. During the first part of flight test, no unexpected behavior occurred. Both systems (the drone and the gripper) performed without any complications and the gripping system could be easily opened and closed mid-flight. The next step was to perform a simple aerial gripping test using a Holybro X500 [4] as intruder drone. It is a commercial DIY kit quadcopter weighing 1,7 kg with a diameter of 50 cm. The intruder drone was held in position while the drone with the gripper was approaching it from below. Once within range of the gripper, the mechanism closed and the drone was successfully captured. Due to the

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[3] Due to internal project reasons, the carrier drone system was changed from a hexacopter to a quadrocopter

[4] https://holybro.com/products/x500-v2-kits

Fig. 12. First manual flight test with gripping system.

soft interception, the intruder drone was not significantly damaged: the motors went into the net, and some of the propellers were damaged upon contact with the arm. All flight maneuvers at this stage were performed manually. To open or close the gripper, the pilot simply pulled the switch to the corresponding position. Figure 12 shows the intruder drone being captured in mid-flight.

V. LESSONS LEARNED

This section will cover three principal insights gained during the development and building of the gripping systems:

A. Think outside the box: It is easier said than done. From today's perspective, the advantages of the "pull" design seem obvious. Because we used rods in the first prototype and mounted them in a certain way, we did not even consider changing our method. Fortunately, we did not spend much time on it before the idea of the "pull" design came to us. Lesson learned: Each problem has more than one possible solution, so rather than trying to "push" one solution, simply "pull" alternatives into your design process.

B. Mechanical designs are not as straightforward as they might appear: Our goal was to build a gripping system that would work based on a simple mechanical principle. The first problems with the design, which included springs, arose when we tried to make it work. Lesson learned: The devil is in the detail. You have to implement small design features (such as a ratchet, dog box and pulley system) to make it workable, and then iron out all the teething problems. This takes time, so you have to be prepared for that.

C. The use of 3D printing and its materials has constraints: Mechanical designs with pre-tensioned elements (such as springs) and moving parts will experience stresses within their components. This can result in misalignment of the axes, separation of the parts and overall twisting of the gripper's frame. Lesson learned: Do not underestimate the flexibility of the printing materials, and try to prevent these issues through clever design solutions. The printing resolution/quality is also a factor that should always be kept in mind.

VI. CONCLUSION

In this paper, we describe an iterative approach to developing a drone gripping system for civil applications. First, we provided a brief literature overview of existing gripping systems. It was clear that the topic is complex and multifaceted, and that the research field is wide open, providing different kinds of possible gripping systems and robotic manipulators. Then, we described our motivations, the pros and cons of the gripping system as well as our inspiration source for the gripping system (*Drosera glanduligera*). Then, we presented our iterative development process for the various components of the gripping system, step-by-step disclosing our implemented design solutions and the logic behind them. During this development process, the system underwent a successive increase in technical complexity, evolving from basic rod-based arm designs to a complex system with dog box and pulley network. After building the functional prototype using rapid prototyping technology, we realized that it did not satisfy the mass requirements. Estimating the use of other materials did not produce positive results. For this reason, we redesigned the activation method and gripping system to use servo motors to actuate each arm. Finally, the gripping system was assembled and successfully tested in the lab and during manual interception flight tests.

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