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A Passive Closing, Tendon Driven, Adaptive Robot Hand for Ultra-Fast, Aerial Grasping and Perching

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***Abstract*— Current grasping methods for aerial vehicles are slow, inaccurate and they cannot adapt to any target object. Thus, they do not allow for on-the-fly, ultra-fast grasping. In this paper, we present a passive closing, adaptive robot hand design that offers ultra-fast, aerial grasping for a wide range of everyday objects. We investigate alternative uses of structural compliance for the development of simple, adaptive robot grippers and hands and we propose an appropriate quick release mechanism that facilitates an instantaneous grasping execution. The quick release mechanism is triggered by a simple distance sensor. The proposed hand utilizes only two actuators to control multiple degrees of freedom over three fingers and it retains the superior grasping capabilities of adaptive grasping mechanisms, even under significant object pose or other environmental uncertainties. The hand achieves a grasping time of 96 ms, a maximum grasping force of 56 N and it is able to secure objects of various shapes at high speeds. The proposed hand can serve as the end-effector of grasping capable Unmanned Aerial Vehicle (UAV) platforms and it can offer perching capabilities, facilitating autonomous docking.**

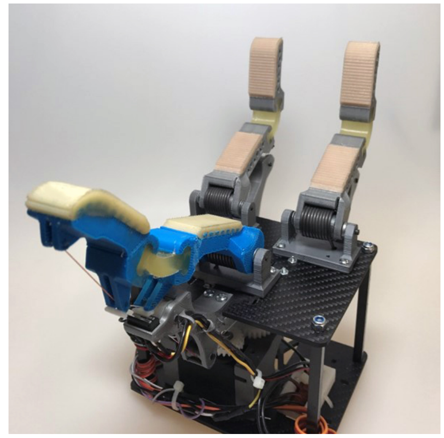

Fig. 1. The developed adaptive, passive closing robot hand. The hand consists of three fingers and uses a cable driven actuation system and a quick release mechanism that allows for ultra-fast grasping speeds (the hand closes in 96 ms) without sacrificing strength (maximum payload is 56 N). A distance sensor is used to detect the objects to be grasped.

I. Introduction

Robots are rapidly becoming part of our lives and they are constantly challenged to execute dexterous tasks in dynamic, unstructured and human-centric environments. The most prominent way of robots to interact and alter their surroundings is via grasping and / or manipulating everyday objects or parts of the environment (e.g., a button of a console, the handle of a door). During these interactions, stability of grasps should be guaranteed and an appropriate set of contact forces should be exerted. The classic approach for solving such interaction problems involves fully-actuated, expensive, multi-fingered, rigid robot hands that are heavy and bulky, that are equipped with several actuators and that require sophisticated sensing elements (e.g., tactile sensing) and complicated control laws (e.g., compliance and impedance control schemes).

Over the last decade, a lot of effort has also been put into designing adaptive, compliant and underactuated hands for robust grasping [1], [2] and dexterous, in-hand manipulation [3]. The use of under-actuated mechanisms and joint compliance robustifies their performance allowing them to grasp objects even under significant object pose uncertainties and their structural and actuation minimalism significantly simplify the control and the planning problems. Similarly, soft robotic grippers [4] also exhibit high structural compliance allowing them to be used in unknown and unstructured environments with minimal control complexity. However, the grasp force and the precision of such systems suffer as discussed in [5]. Thus, adaptive hands are an excellent alternative to the fully-actuated, rigid robot hands that are typically used for dexterous tasks. Traditionally, for the creation of adaptive hands, structural compliance is introduced either in the joints (e.g., flexure joints) [6] or in their finger-pads [7], increasing the mechanical adaptability / conformability of the overall grasping mechanism.

Regarding possible applications, adaptive hands are typically used for robot grasping and dexterous, in-hand manipulation as end-effectors of full robot arm hand systems, but they can also be used for robotic platforms that require a lightweight solution that provides increased robustness (e.g., Unmanned Aerial Vehicles (UAVs) / drones that have minimal payload capabilities). For such platforms an increased end-effector weight, increases power consumption, decreasing their operation time and their range. Thus, the only really viable solution is an underactuated, simplified design that requires minimal power consumption. Furthermore, the use of a passive closing approach further reduces power consumption. Many companies intend to use drone technology to deliver packages in 30 minutes or less [8]. However, these drones require human help to load and unload the packages and the system is not truly autonomous. Current UAV mounted grasping methods are slow, inaccurate, and have specific environmental and geometric constraints.

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In this paper, we propose a lightweight gripper, which utilizes tendon driven underactuation schemes, passive elastic elements, and a quick release mechanism. The system allows the execution of ultra-fast aerial grasping for dynamic object grasping and drone perching. The device is experimentally tested through three different experiments: i) palm configuration efficiency for determining the optimal finger base frame configuration for grasping, ii) a perching weight test, and iii) grasping of various everyday life objects.

The remainder of the paper is organized as follows: Section II discusses the related work, Section III presents the design on the proposed robot hand, Section IV details the experiment setup and discusses the results, while Section V concludes the paper and presents some potential future directions.

II. Related Work

Traditionally, research in the field of robot hands has been conducted with the goal of "mimicking the human anatomy and physiology" [9]. Despite this, the existing developments in the field of robot hands design do not match the human hand performance [10]. As the dexterous capabilities of a robot hand increase, so does the mechanical and control complexity, the weight, and the power consumption. Over the last ten years, a new class of adaptive robot hands has emerged that facilitates the execution of stable grasps in unstructured environments even when the object properties are not known or accurately predicted. This attribute of adaptive hands is due to the under-actuation (the use of less motors than the available degrees of freedom) and their mechanical compliance that allows them to conform to the object surface [1], [11].

The idea of using simple, underactuated robot hands for dexterous tasks is not new. Bicchi et al. [9], first summarized the evolution of robot hand designs and made a critical evaluation of the core ideas and trends, distinguishing between hands designed for mimicking the human anatomy / physiology and hands designed to be as functional as possible. Moreover, Bicchi et al. presented a series of arguments favoring a "minimalistic" approach in designing robot hands (e.g., using a limited number of actuators), discussing also the problems that roboticists may face during this challenge.

Over the last decade, various designs of adaptive hands have been proposed that facilitate the execution of robust grasping and dexterous manipulation tasks. These designs exhibit some form of structural compliance (e.g., joint, fingertip, or finger-pad compliance) and most of them are also underactuated (have less motors than the available degrees of freedom). An underactuated design provides simplicity in operation and control and it requires significantly lower development cost and power consumption as the number of motors is minimized. Significant research effort has also been put into investigating alternative hand geometries and kinematics that led to non-conventional hand designs, especially for imparting in-hand manipulation capabilities. There has been also significant effort in making those hands freely available, using an open-source dissemination and providing adequate documentation for design replication [1], [2], [6].

Regarding aerial grasping, in [12] the authors provide insight into the specific performance of robotic hands for aerial manipulation. Many existing prototypes directly use or draw inspiration from the Shape Deposition Manufacturing (SDM) hand design [1]. For example, [13] uses a modified SDM hand attached to an RC helicopter to grasp grounded objects from an unstructured environment while the helicopter was in flight. The lightweight, cost effective adaptive hand presented in [6], used a 2 finger grasper attached to a UAV in a small section of its experimentation. A simple Lego version of the SDM hand is presented for indoor autonomous aerial grasping in [14] and the perching foot in [15] also draws inspiration from the same design. The avian-inspired grasper developed in [16] utilizes aspects of the Shape Deposition Manufacturing (SDM) design [1] and the Festo EXOhand [17] to grasp cylindrical objects at high speeds.

In [13], the authors presented the performance of a grasping capable helicopter that was equipped with a gripper weighing less than 750g. The setup was experimentally validated by autonomously hovering the helicopter over an object, and grasping it. However, needing to hover over objects during payload acquisition increases the power consumption and flight time of a UAV. The high speed avian grasper in [16] minimizes this by performing high speed collection of a cylindrical object that weighs 27g from a table surface while flying at a speed of 2m/s. In [14], a stuffed toy was placed below the autonomous indoor UAV platform and it was located using an IR light on the toy. Then altitude was decreased to target height determined by the perceived size of the IR light, the object was grasped and the UAV returned to a hover within 4 sec of the initial sighting. Similarly to the avian grasper, a 2 fingered gripper was also employed, which limits the types of possible objects that can be grasped. Whereas in [13], the use of the SDM hand offers adaptive grasping increasing the range of possible objects that can be grasped. Although these UAV platforms are able to execute aerial grasping, the grippers used rely on active actuation from an actuator to maintain a grasp on an object. The prolonged grasping of an object with such a gripper can lead to high power consumption reducing the total possible flight time.

Regarding perching, the design in [15] was inspired by songbirds, as their feet grasp a branch tighter as the bird relaxes and puts weight on its legs. This design implements passive grasping by converting the perched weight of the UAV platform into adequate tendon tension that closes the gripper, ensuring a stable perched state. Another approach is to use microspines [18] which dig into the perching surface to suspend the UAV, or a suction cup [19] which uses aerial impacts to perch on smooth surfaces. Although all these systems provide passive forms of perching in different scenarios with no power consumption in the perched state, the mechanisms cannot double as a gripper to grasp objects while the drone is in flight. This adds additional weight and reduces the maximum payload capacity a drone can carry.

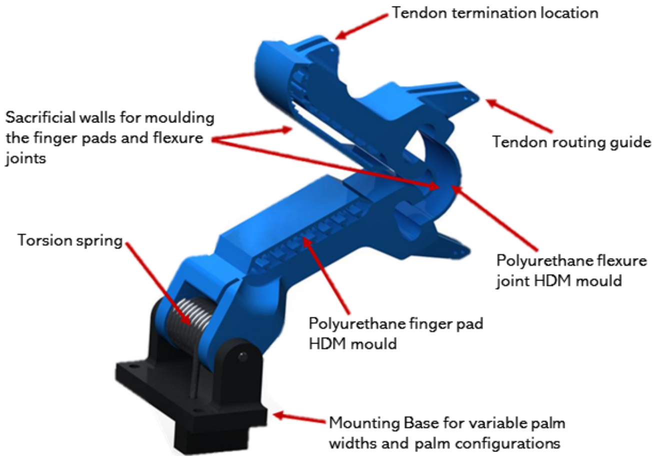

Fig. 2. The structure of a passive-closing adaptive finger before moulding. The finger is tendon driven and it has a spring loaded pin joint and a flexure joint. The flexure joint and the finger pads are based on polyurethane elastomer material (Smooth On – PMC 780 and Vytaflex 30), which is poured in between the sacrificial mould walls using the concept of Hybrid Deposition Manufacturing (HDM) [21].

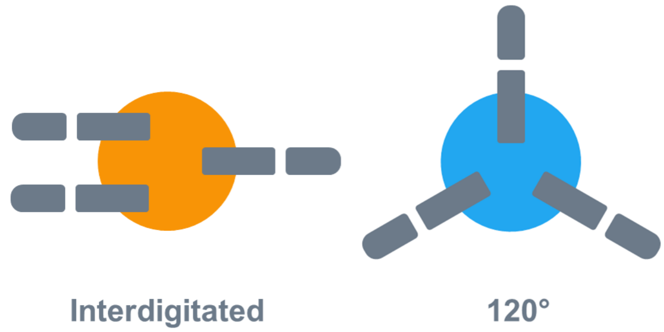

Fig. 3. The different palm configurations considered.

The current state of the art of aerial grasping systems presented here has two key limitations. Firstly, as demonstrated in the case of the Yale aerial manipulator [13] and the autonomous indoor grasper [14], a major limitation is speed. Although a lot of development has been put into ultra fast robotic grasping [20], such systems are not specifically designed for UAVs. This is due to the weight and payload limitations of aerial systems that restrict the choice of actuators and the potential actuation speed of an active closing hand. Implementing a passive-closing grasper may benefit not only the speed of the device but also it can reduce the power consumption, increasing the operation time and augmenting the perching and grasping capabilities of the system. Secondly, their inability to grasp a wide range of objects limits their applicability in real scenarios, as discussed in [15].

III. Designs

In this section, the design of a passive closing, tendon driven, adaptive hand is presented. The device consists of three fingers, a hand base, and a quick release mechanism. The hand base houses the electronics consisting of a microcontroller (Arduino Nano), a limit switch, an IR proximity sensor (Sharp GP2Y0A21YK), a high torque metal gear servo motor (ym-2763), and a micro servo motor (hxt900). The total weight of the system is 551 g.

A. Robot Fingers

The robot fingers designed for the proposed passive closing, adaptive robot hand are created using the concept of Hybrid Deposition Manufacturing (HDM), as discussed in [21]. The robot fingers consist of two phalanges per finger and their joints are implemented with a spring loaded pin joint at the metacarpophalangeal joints (MCP), and a polyurethane rubber (Smooth On – PMC 780) flexure joint at the distal interphalangeal joint (DIP). The finger pads are constructed from a polyurethane rubber (Smooth On - Vytaflex 30) to increase friction between the finger and the object during object grasping. The fingers are developed in a pre-shaped position as depicted in Fig. 2. Thus, each finger is initially flexed when not actuated and then when the extensor cable is pulled the finger starts extending, storing energy in the elastic joints before it gets released to execute ultra-fast grasping. Tendon routing guides incorporated along the back of the finger displace the tendon further away from the joints offering a mechanical advantage, and prevent derailing of the tendon during extension and flexion.

B. Hand Base

The proposed design uses a modular hand base for design optimization purposes, which allows the fingers to switch between interdigitation (two fingers face the third) and a symmetrical design that positions the fingers every 120 degrees. The different finger configurations are depicted in Fig. 3. Alongside this, variations between finger base distances are also accommodated. At the center of the hand base is an IR proximity sensor for sensing when objects are within the grasping range of the hand. Several experiments were conducted with different finger base positions by mounting the fingers in different configurations on the finger base structure. Results are reported in Section IV where all the experiments are presented. The hand base has also been appropriately designed so as to allow fast mounting on certain UAVs / drones.

C. Quick Release Mechanism

In this subsection, we present the quick release mechanism that allows the execution of ultra-fast grasps by the developed adaptive robot hand (the achieved hand closing time is less than 96 ms). The mechanism is designed to be compact and light-weight with minimal friction. It uses a very light, 9 g servo to initiate the quick release and it has been fabricated using laser cutting and precision 3D printing. The device employs a simple dog collar gear engagement; an internal coaxial shaft holds the dog collar engaged or disengaged via a micro servo attached to the bearing cap. During engagement a secondary high torque motor winds the gear, which is linked to the dog collar, turning the external shaft and the tendon drum to extend the fingers open. This opening action

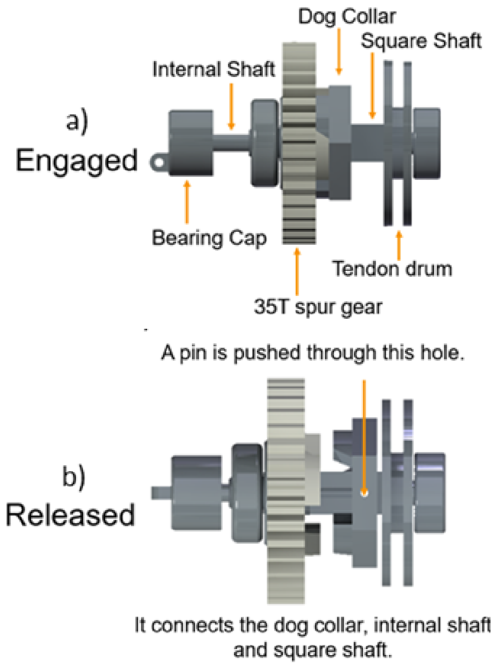

Fig. 4. 3D models of the quick release mechanism developed for the passive closing, adaptive robot hand. Subfigure a) presents the mechanism in *Engaged* configuration where the dog collar is in contact with the spur gear through the internal shaft allowing rotation of the tendon drum to open the gripper, while Subfigure b) presents the mechanism in *Released* configuration where the internal shaft has disengaged the dog collar from the spur gear.

takes 11 seconds to full open the gripper. When the bearing cap on the left side of the quick release mechanism of Fig. 4 is pressed (this action is completed by the micro servo) the dog collar gets disengaged and the tendon drum can turn independently of the gearing and the high torque servo. The model of the quick release mechanism is depicted in the two different configurations in Fig. 4.

IV. Experiments & Results

In this section we present the apparatus used, the experiments conducted and the results that validate the efficiency of the proposed robot hand.

A. Palm Configuration Results

A grasp test was implemented to determine the best palm configuration design. The hand attempted to grasp three different objects (a screwdriver, a tennis ball, and a water bottle) 15 times each. To simulate dynamic grasping on a drone, a swing pendulum with a cable attached to one of the three objects ensured a repeatable trajectory in which the object would travel towards the static gripper for grasping. This was completed for both palm configurations. The interdigitated configuration achieved 81% grasp success compared to only 67% for the 120 degree configuration. Thus, an interdigitated design was chosen for the grasping experiments.

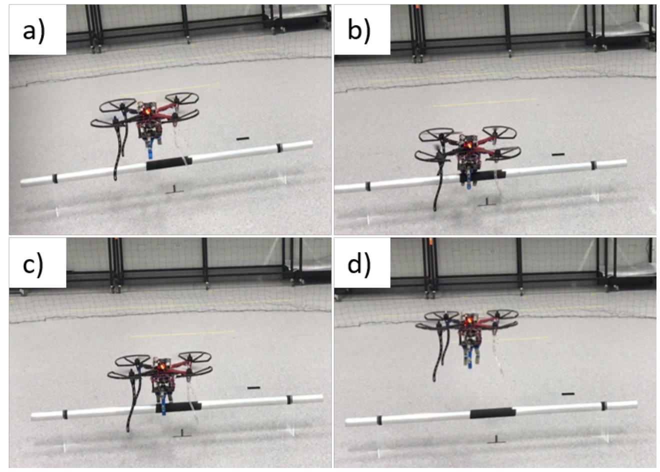

Fig. 5. The proposed aerial gripper is depicted performing a perching task with a drone landing on a pole and then taking off. The actions performed occur, as follows: a) the drone approaches to dock, b) aerial gripper successfully closes executing perching, c) gripper is opening to allow take off, d) the drone has fully taken off.

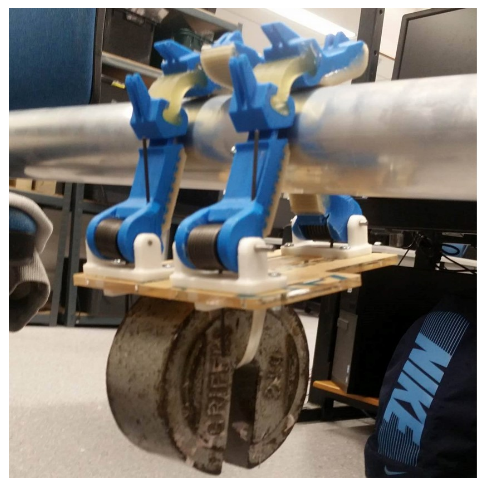

Fig. 6. The proposed passive closing, adaptive robot hand in interdigitated configuration perching on a pole, supporting a 2 kg weight.

B. Perching Experiments

The hand was tested on a quadcopter (DJI F450 Flame Wheel drone) and was able to perch on an aluminum bar and take off again (Fig. 5). Prior to the flight test two other perching experiments were conducted on a 48 mm diameter aluminum poll. The first experiment was to determine the maximum weight the gripper could support. This was done by perching on the pole upside down with different palm configurations, finger base frame distances, flexure joint thicknesses and spring coil angles while supporting various weights (see Fig. 6). The results from this experiment (Fig. 7) showed that the maximum interdigitated configuration was able to support 3.5 kg, while the 120 degree configuration was able to support 5.22 kg highlighted in black on Fig. 7. Although the interdigitated design has proven to be better from a object grasping perspective, the 120 degree configuration has better perching capabilities.

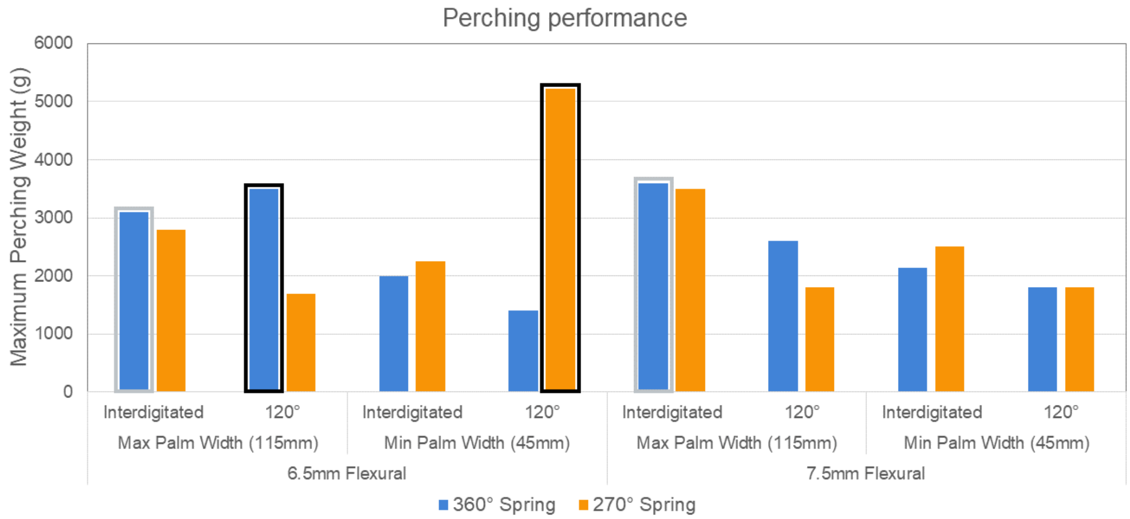

Fig. 7. The results of the perching experiments conducted that include the weights supported for the different palm configurations. Two different flexure joint designs were considered. The first had a thickness of 6.5 mm while the second has a thickness of 7.5mm. This variation did not show any significant differences in the results. However, variations in the palm width (distance between the finger base frames), finger configuration, and spring coil angle displayed a significant result in the maximum perching weight the the robot hand could achieve.

Fig. 8. The passive closing, adaptive robot hand performing ultra-fast grasping of: a) a marker flying towards the outer edge of the gripper's workspace indicated by the orange circle, b) a plush toy (teddy bear), and c) a aluminum drink can.

The second experiment conducted, was a perching angle test to determine how much pitch angle a drone can have during an autonomous docking task. The robot hand was attached to the quadcopter and was angularly displaced from the upright position. The maximum angle displacement was achieved by the interdigitated configuration with an angle displacement of 10 degrees from the upright position. Thus, the hand facilitates autonomous docking via perching even in the presence of drone angular positing errors caused by external disturbances (e.g., wind).

C. Grasping Experiments

For the grasping experiments 8 objects (a water bottle, a screwdriver, a tennis ball, a hat, an energy drink can, a marker, a 15 cm diameter large tube, and a teddy bear) were tested and were successfully grasped. Fig. 8 shows that grasping is extremely robust to object position uncertainty. The marker pen is on the very edge of the hand span contacting the distal link near the end. However, due to the speed and adaptive nature of the hand, the marker pen is still grasped successfully.

D. Videos and Supporting Data

A wide range of videos and supporting data that validate the efficiency of the proposed passive-closing robot hand designs can be found in the website of the New Dexterity research group at the following URL:

www.newdexterity.org/aerialgrasping

The particular videos involve a variety of everyday life objects in completely dynamic "on the fly" grasps. In certain cases the objects are thrown towards the robot hands at high speeds.

V. Conclusions and Future Directions

In this paper, we proposed a new, simplified solution to the UAV-based aerial grasping problem, by developing a passive closing, adaptive robot hand that can be mounted to such a platform and which can achieve ultra-fast grasping of everyday objects, using a quick release mechanism and distance sensor. More precisely, initially we focused on the design and development of the adaptive robot hand. Then, we presented the quick release mechanism that facilitates the implementation of ultra-fast grasping motions and we discussed the role the infrared (IR) sensor that enables the gripper to identify the objects to be grasped from a distance, triggering the grasping motion. According to the experiments conducted the hand can achieve a grasping time of 96 ms, a maximum payload of 56 N and it is able to grasp a variety of everyday life objects at high speed, as end-effector of UAVs or other robotic platforms. The hand can also facilitate the execution of autonomous docking tasks via perching.

Regarding future directions, we plan to further improve the efficiency of the proposed robot hand by reducing the weight and increasing the speed of the grasping process. Moreover, we plan to integrate the hand on a Drone and perform autonomous aerial grasping experiments.

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