2023 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)
June 28-30, 2023. Seattle, Washington, USA

A Linkage-Based Gripper Design with Optimized Data Transmission for Aerial Pick-and-Place Tasks

Sean Smith, *Student Member, IEEE,* Scott Buchanan, and Ya-Jun Pan, *Senior Member, IEEE*

Abstract— **Aerial grasping is beginning to revolutionize industrial applications through robotics in Industry 4.0. However, this sector still lacks a gripper mechanism effective in autonomous grasping of in-house cargo and simple enough for rapid generation and implementation on a variety of industrial drones. A novel four-bar linkage rigid gripper was developed to address these challenges. This gripper is constructed of lightweight multi-material 3D printed components facilitating rapid construction and designs. The linkage setup allows for easy scaling while modular end effectors optimize performance for varying gripping applications. Manual gripping tests along with autonomous pick-and-place missions were conducted to evaluate the overall performance. The results demonstrate viability and point towards design adjustments and robust control algorithms for improved autonomous grasping under ground effect. The gripper in this work was designed and tested on the COEX Clover Drone available in the host lab. Its design can be extended and adjusted to any other aerial vehicles in general.**

I. INTRODUCTION

The implementation of Unmanned Aerial Vehicles (UAV) for industrial applications has surged in recent years. UAVs are known to be proficient in tasks involving navigation and perception such as facility inspection, security, science data collection, and military reconnaissance. However, recent developments using UAV load transportation systems has demonstrated aerial robotics can effectively and efficiently transport a payload.

Factories have begun to take advantage of this as automation continues to evolve with the objective to realize smart and efficient production [1]. Delivery drones have started to push forward Industry 4.0 by providing rapid and flexible logistic solutions with facility operations. Examples of this include effective human-machine collaboration "cobot" where UAVs work alongside humans to produce an undisrupted flow of components, products and workstations to their intended destinations within the facility. They extend the flow of materials by benefiting from high rise infrastructures that provide sufficient airspace for the transportation of intralogistics.

Accomplishing this requires active interaction through UAV pick and drop applications. In order to avoid the high degree of actuation, complexity, and additional mass caused by robotic manipulators [2], low degree-of-freedom (DOF) grippers directly attached to the UAVs are used in many aerial grasping tasks [3]. Facility environments involve transportation of packages including standard boxed cargo with set sizes and loads [4] along with various tools to assist operators within the facility. Based on these applications, the key attributes for the gripper design are lightweight, robust, scalable, adaptable, and the ability to grasp and transport securely and safely.

With these common applications and design criteria, we developed a novel aerial gripper for UAV load transportation that exhibits light weight parallel actuation based on a scalable four-bar linkage design. It is targeted for autonomous transportation of industrial tools and small scale standardized boxed payloads with potential applications in smart factories.

Aerial gripping poses a wide range of challenges including positional inaccuracies, physical and energy constraints, disturbance handling and the ability to grasp a variety of objects [5]. To compensate for positional inaccuracies and contact forces, passive mechanical compliance is introduced [6] where a large self-centering work envelop is also considered [7]. Some grasping applications use optical tracking systems to mitigate positional inaccuracies [8]. Energy conservation is considered in [9] using magnetism and high holding forces. In-house cuboid object transportation has been considered [10] although autonomous transportation remains a problem. Many of these works have compliance and adjustability in mind, however efficient setup adaptability is not explicitly addressed.

Soft robotics [11] is being integrated with grippers to minimize contact forces in high speed grasping [12]. Coupling this with 3D printed technology [13] has forwarded an improved design strategy for aerial transportation. However, a large DOF system is complex while modeling and optimization can be difficult. Linkage designs remain common in manipulation [14], [15], where this highly developed area is found in UAV perching [16] and gripping [17]. The scalability and adaptability of linkage designs provide 6-DOF solutions for precision grasping [18], [19] using parallel actuation [8]. Although in these cases, a high degree of actuation makes adaptability challenging.

In light of this discussion, we adopt a 3D printed four-bar linkage design into a rigid gripper controlled by a single servo motor. The parallel concept is implemented in the form of parallel plates capable of transporting standard factory

---

This work was supported in part by the funding from the Natural Sciences and Engineering Research Council (NSERC), and the Government of Nova Scotia, Canada.

Sean Smith, Scott Buchanan, and Ya-Jun Pan are with the Department of Mechanical Engineering, Dalhousie University, Halifax, Canada, B3H 4R2. (e-mails: `s.smith@dal.ca`, `scott.buchanan@dal.ca`, `yajun.pan@dal.ca`).

978-1-6654-7633-1/23/$31.00 ©2023 IEEE

objects. The linkage setup makes it scalable and the low degree of actuation allows for repeatable and adaptable implementation. The overall system including the drone, light weight gripper, and time synchronized data transmission system is targeted to allow for fully autonomous indoor pick-and-place tasks. Extensive experimental studies are carried out to verify the functions of the gripper and the seamless integration with the Clover drone.

II. SYSTEM ARCHITECTURE

A. System Components

The drone used for experimental testing is the COEX Clover 4.2 shown in Fig. 1. Like many drones used in research it consists of open source off-the-shelf components that allow us to modify and test new designs and algorithms. The entire system responsible for autonomous missions can be divided into three distinct subsystems as in Table I.

TABLE I

EACH SUBSYSTEM AND ITS CORRESPONDING COMPONENTS.

Clover	Gripper	Offboard
Raspberry Pi 4B (Companion computer)	Dynamixel XL330-M288-T Servomotor	4 OptiTrack Flex 13 cameras (Motion capture data)
COEX Pix (Flight Controller)	Robotis U2D2 (USB communication)	Laptops/PCs (System analysis, data transfer and logging)

III. GRIPPER DESIGN

A. Mechanical Design

We explored a variety of mechanical kinematic designs before taking inspiration from the four-bar configuration [20]. The main design characteristics considered are:

- Total Weight;
- Scalability/Adaptability and Robustness;
- Fabrication;
- Secure Transportation.

Using a multi-linkage mechanism allows for increased scalability and adaptability within the Clovers physical constraints. The total workspace is reduced compared to lower linkage systems [21]. Based on a maximum takeoff weight of 1 kg provided by COEX, it was determined an additional 300 g could be added including the gripper and target object. The final gripper design can be seen in Fig. 2 in its open position. It is actuated by a servomotor connected to the onboard Raspberry Pi. The gripper has three distinct components: a pushbar mechanism, a four-bar linkage, and a modular gripping face.

- **Push-bar:** A push-bar mechanism was constructed to convert the horizontal plane motor rotation into the vertical plane motion. The push-bar is driven through a ball joint by a centerpiece that was designed to connect to the Dynamixel motor via four connection pins. The push bar connects to the end link of the four-bar linkage by a second ball joint.
- **Four-bar:** The four-bar linkage was constructed through two pairs of equal length linkages at 3 cm. This ensured opposing linkages were parallel to each other at all motor positions allowing for parallel gripping faces.
- **Modular gripping face:** The face of the gripper was designed to be modular which allows for adaptive end effector designs. This also provides for design adjustments when adapting to new drones and environments.

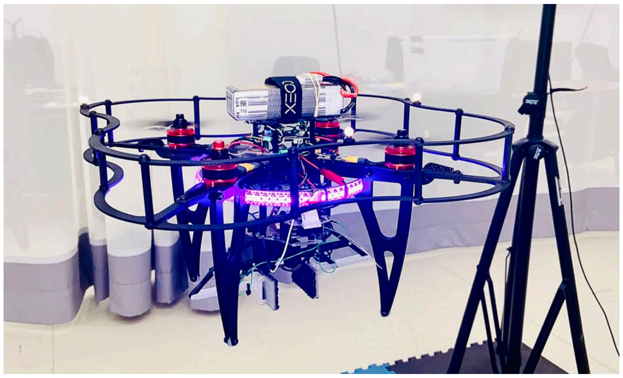

Fig. 1. COEX Clover 4.2 with linkage gripper in flight.

1) Parallel Plates: The four-bar linkage setup allows for modularity by adjusting dimensions. To take advantage of parallel actuation in the current setup, parallel plates were used for gripper-object interaction. This guarantees that the available gripping surface is in contact regardless of the motor position.

2) Fabrication: The frame and linkages of the gripping mechanism are 3D printed out of PETG as it provides a strong, durable, and resistive material for reliable transportation under varying loads. The center piece was 3D printed out of resin because the strength and rigidity of the material allowed four small pins to be 3D printed into the piece and connected to the motor. This rigidity also allowed the ball joints in the gripper to be reliable and not prone to disengaging. The pins used in all of the linkages were made of small 1.2 mm brass rods. A rubber mesh was used on the parallel plate gripping surface as increased friction is needed with flat surface contact for secure grasping.

B. Software Design and Control Architecture

The gripping mechanism is actuated by a python control module on the Raspberry Pi using position-torque mode with defined applied torque and encoder positions. This is ideal for articulated robots and grippers. The internal control architecture features a Proportional Integral Derivative (PID) controller with feedforward components to improve profile tracking. Communication between the Raspberry Pi and Dynamixel motor was accomplished through the use of a U2D2 converter.

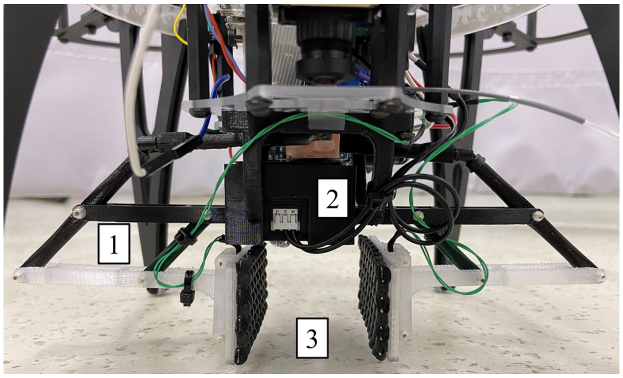

Fig. 2. Mechanical gripper; 1) four-bar linkage; 2) servomotor; 3) parallel plate actuation.

IV. POSITION TRACKING AND CONTROL

A. *Onboard Control*

Onboard the COEX Clover is a flight controller that runs PX4 and communicates with the Raspberry Pi 4B over a universal asynchronous receiver-transmitter (UART) serial connection. The Raspberry Pi handles computation and communication between Robot Operating System (ROS) and the flight controller through the MAVLink protocol. Clover pose data is forwarded using this protocol and PX4 uses an Extended Kalman Filter (EKF) state estimator to fuse the external vision pose with the onboard pose estimation. The EKF runs on fusion time horizon to compensate delays.

Trajectory generation for the autonomous missions is computed through Clovers 'simple offboard' module provided in the Clover package [22]. This module is setup to generate position setpoints at 30 Hz continuously throughout the entire mission referencing the Clover and target objects pose. PX4 implements a control system based on a cascaded control structure which is popular in quadcopter dynamic control. It consists of linear PID controllers. The controllers contain two loops where the inner loop is the attitude control module comprising a nonlinear P attitude controller operating at 250 Hz and a PID angular rate controller operating at 1000 Hz in the body frame. While the outer loop is the position control module consisting of the P position controller and PID velocity controller operating at 50 Hz in the inertial frame. The inner control loop was tuned using an indirect adaptive tuning module provided by PX4 [23] and the outer control loop was fine-tuned using manual iterations.

B. *Offboard Control*

Visual feedback for the Clover and the target object are provided by an Optitrack Motion Capture System in Fig. 5. During flight, Optitrack cameras capture the tracker motions, then stream the data at a rate of 120 Hz. For the setup in Fig. 3, pose data is then fed to the Raspberry Pi using a custom User Datagram Protocol (UDP) client-server written in C++ that runs a thread and waits on data packets provided by the NatNet IP multicasting server. These data packets are then received by the client socket on the Raspberry Pi, processed into pose data and sent to the flight controller using ROS. A ground station computer is used for a variety of purposes that are listed:

- Connects to the Raspberry Pi to activate the custom UDP client as well as a python script that starts the autonomous grasping mission.
- Operates as a self-check device by analyzing onboard functions and the communication between MAVROS and the PX4 using Clovers self-check function.
- Communicates with the Clover over a multimachine ROS network. This is used to analyze the EKF external pose data fusion by inspecting MAVROS topics in Rviz.
- It acts as a ground station for flight data logging and analysis, PX4 firmware modification and controller tuning using QGroundControl.

Each computer in the setup interacts using a time synchronized local network using a network time protocol server on the motion capture system computer with a dynamic host configuration protocol server for communication.

V. EXPERIMENTAL RESULTS

A. *Gripper Setup and Results*

The gripper was tasked to hold a variety of tools. The process involved placing the Clover on the ground, centering the object within the gripper, gripping it, then manually translating the Clover 0.5 m in each direction before landing again. This procedure was performed 10 times for each object in Fig. 4. The object mass and gripper performance results are listed in Table II.

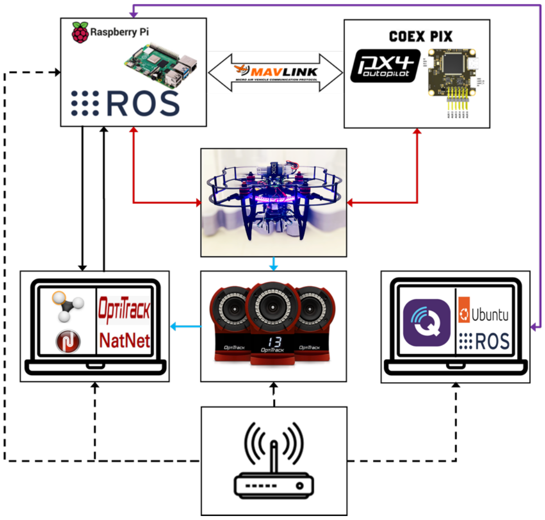

Fig. 3. Experimental setup topology. Legend: Black dotted line is the provided local network; Black solid line is the UDP client-server drone pose transmission; Light blue line is the pose data transmission; Red line is hardware connections; Purple line is communication via secure shell protocol and ROS network communication; MAVlink arrow is communication via a MAVlink protocol.

TABLE II

GRIPPER PERFORMANCE GRASPING VARYING OBJECTS.

Object	Mass (grams)	Success Rate
Lock	151	100% (10/10)
Pliers	241	100% (10/10)
Toolbox	185	100% (10/10)

Based on the results, the gripper was able to provide a sufficient parallel plate clamping force to transport each object. Additionally, hover flight tests were conducted under these conditions with a video in Section V-C. It was determined the Clovers onboard control and stability could manage relatively stable hovering up to 151 g, where 185 g showed frequent oscillations and 241 g compromised stability although this far exceeds the design limitations of 180 g. This highlights the limitations of PID controllers which use the integral term to compensate for additional unknown loads [24].

Another concern is the reliability of contact forces when transporting objects of varying shapes and sizes with wearing parallel plate friction. This can be alleviated by trading complete force closure with form closure grasping [25]. Future considerations will involve the replacement of parallel plates with ones that produce a form closure to ensure increased safety and reliability when transporting heavier objects.

B. System Setup and Coordinate System

The experimental environment in Fig. 5 has a drop zone labelled by an ArUco marker, this is the starting and end point of the mission. The Styrofoam target object was labeled with OptiTrack facial markers to provide a target pose for the Clovers onboard server. The coordinate system is set as an X East, Y North, and Z Up (ENU) system whereby the x-axis corresponds to longitudinal translation and y-axis corresponds to the lateral translation relative to the target object. ROS uses the same coordinate system and transforms data to the North East Down frame for the PX4 control system.

Fig. 4. Testing objects found in factories of varying shape, size, and material. a) Toolbox b) Lock c) Pliers

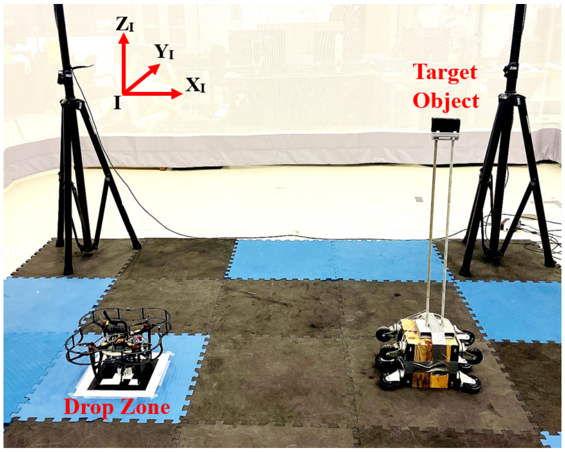

Fig. 5. Experimental setup including the Clover, drop zone, target object and coordinate system of motion capture volume.

C. Results

A series of twenty autonomous grasping missions were conducted to analyze the performance of the gripper and hardware design framework. These autonomous missions are separated into three phases:

- **Phase 1:** Takeoff 1.42 m above the drop zone {−0.32, −0.024, 1.42} m at 0.5 m/s. Track to a waypoint {0.835, −0.014, 1.42} m located directly above the target object at 0.25 m/s and align with 0°yaw reference.
- **Phase 2:** Descend to {0.835, −0.014, 1.145} m at 0.1 m/s while maintaining 0°yaw reference. Close the gripper to grasp the object before ascending above the pickup location {0.835, −0.014, 1.42} m at 0.5 m/s.
- **Phase 3:** Track back to a waypoint directly above the drop zone {−0.32, −0.024, 1.42} m at 0.5 m/s.
  1) Descend and land into the drop zone before releasing the target object for a successful mission.
  2) For a failed target object retrieval, descend and land into the drop zone.

The position and heading of the Clover during each phase of a successful mission can be seen in Fig. 6. The first phase was used to analyze the drone's tracking performance provided by position and yaw setpoints. The second phase was used to analyze the drone's ability to carefully descend, keep the target object aligned in the grasping volume by maintaining yaw and retrieve the block. The final phase was used to evaluate in-flight load transportation and delivery. The success rate of each section can be seen in Table. III.

TABLE III

SUCCESS RATE OF EACH PHASE THROUGH 20 ITERATIONS IN THE AUTONOMOUS GRASPING MISSION.

Phase	Success Rate
1	100% (20/20)
2	55% (11/20)
3	1) 91% (10/11) 2) 100% (9/9)

Overall, the autonomous grasping missions were not as successful as desired. The first phase was accomplished with every attempt where the Clover accomplished sufficient tracking performance. The Mean Absolute Error (MAE) for position during Phase 1 was {5.2, 0.81, 7.9} cm. The elevated errors with x-position and z-position were from the Clover not tracking the changing setpoints as tightly, although for this application it was more than enough. Also, the Clover was able to maintain a zero-degree yaw towards the end of Phase 1 and into the beginning of Phase 2 for gripper alignment.

The second phase was the most critical one as it involved controlled grasping of the target object. From Table III, it had a 55% success rate and the MAE in position for Phase 2 was {0.81, 0.96, 3.74} cm and the MAE in yaw was 0.28°. While this illustrated a precise controlled descent specifically in x and y, many times the target object was missed. From observation, missed grasps were mainly caused by small deviations in the y-direction. The y-direction corresponds with the lateral portion of the grippers grasping volume being 4 cm wide in its open position. The maximum error in the y-direction was 3 cm during this phase therefore having a relatively small work envelope puts a great deal of pressure on the drones performance to ensure a successful grasp.

The third phase seen a 10/11 success rate as the Clover was able to transport the target object back to the drop zone. The styrofoam weighed 5 g so it had no flight dynamic influence the onboard controllers could not handle.

The video of the experiment can be seen in the following link: `https://youtu.be/P4aa8GVaKMM`.

D. Limitations and Discussion

Based on observations the primary source of failure was deviations in the horizontal plane. This led to the Clover descending with the target object outside of the grasping volume causing missed grasps. When the horizontal setpoint was maintained throughout the descent, the block would enter the control volume before being retrieved. The y-direction consisted of a MAE of 0.96 cm during Phase 2 making it difficult to consistently have the 2 cm wide block enter a 4 cm wide grasping volume. Increasing the work envelope, specifically the grippers open position by a few centimeters, would improve the robustness in positional errors in this setup. The scalability of the linkage design will allow for this.

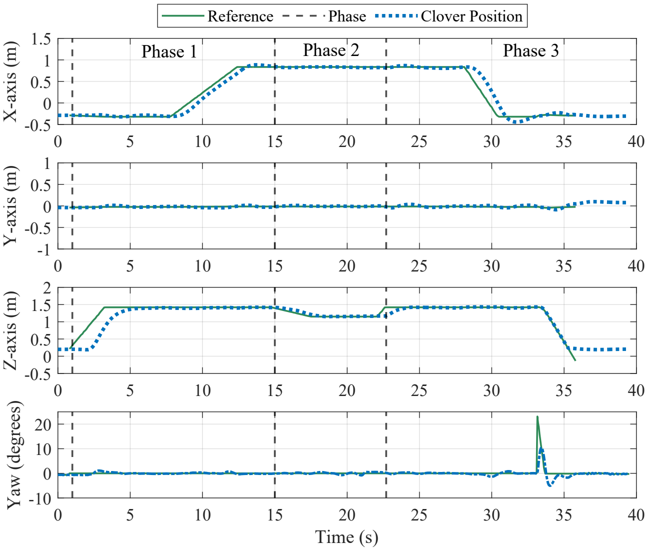

Fig. 6. Profiles of the Clover position and heading tracking during the autonomous mission.

For these experimental tests, only position setpoints were provided to the PX4 control system. While this is sufficient for general linear waypoint tracking, improved trajectory tracking can be accomplished by providing feedforward setpoints. This is primarily used in the complex trajectory tracking although precise tracking when approaching the target object paired with high precision pose feedback from the motion capture system would be beneficial.

The downwash produced by the Clover would have varying effects if the target object was placed lower to the ground. The first being "thrust stealing" effect [12] and the second being an influence of ground effects [26] which destabilizes the quadcopter in low altitude flight because of uncertainty in the drone dynamics (unmodelled dynamics). This was mostly avoided with the elevated target object although, small wind disturbances produced when the Clover slowly descended towards the stand caused increased deviations in the xy-plane.

This uncertainty is not accounted for with the PX4 PID controllers. Control methods such as adaptive [27] or robust [28] will be needed to compensate while operating under time varying external disturbances.

VI. CONCLUSIONS AND FUTURE WORKS

In this article, a 3D printed lightweight multi-linkage rigid gripper was proposed alongside a complete system architecture for indoor aerial pick-and-place tasks. We describe the system architecture in detail, including the gripper design, data transmission, autonomous flight preparation and control algorithms. We evaluate the setup through extensive autonomous grasping tests in a motion capture volume. However, with a 55% object retrieval success rate across 20 trials, several key attributes need to be developed in order for improved performance including; 1) a larger work envelope to alleviate highly precise position tracking required by the drone; 2) a robust and/or adaptive control method paired with improved trajectory generation to compensate for varying disturbances allowing for lower altitude grasping and tighter reference tracking; and 3) end effector redesign to ensure form closure grasping for more reliable industrial application.

While the discussed developments push for improved performance in the current setup, this merely cracks the surface of challenges robotics face with indoor industrial transportation. We will look to eliminate the need for precise

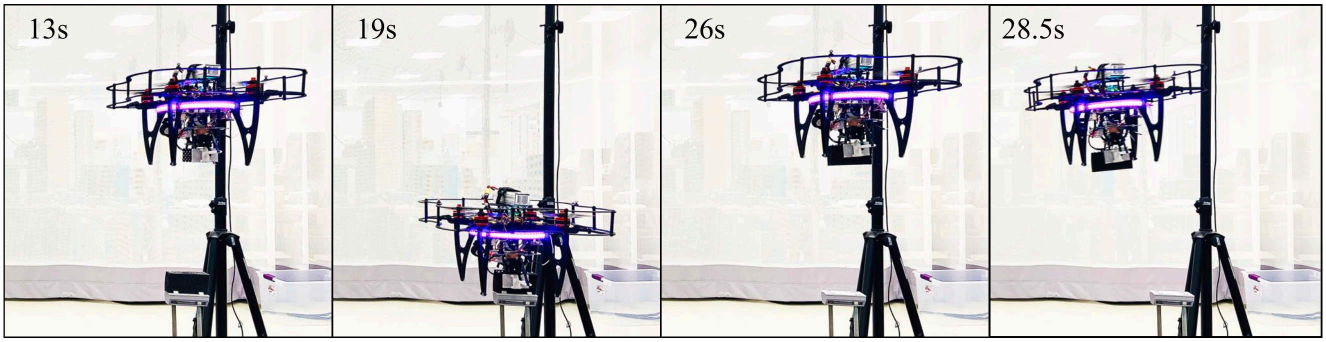

Fig. 7. Phase 2 sequence of the autonomous mission. The Clover reaches the target object, aligns the gripper before descending and retrieving the target object and returning to the drop zone.

motion capture feedback and investigate collaborative load transportation methods with either robot-robot/human-robot interaction that allow for Industry 4.0 applications.

ACKNOWLEDGMENT

The authors would like to thank Dulyavich Vongsathorn, Garret Johnson, and Cole Bleau with the construction of the four-bar linkage gripper prototype.

REFERENCES

[1] A. Fellan, C. Schellenberger, M. Zimmermann, and H. D. Schotten, "Enabling communication technologies for automated unmanned vehicles in industry 4.0," in *2018 International Conference on Information and Communication Technology Convergence (ICTC)*, 2018, pp. 171–176.

[2] A. Mishra and S. Behra, "Design of an aerial manipulation system with robotic claw for search and rescue operations," in *2020 IEEE Bombay Section Signature Conference (IBSSC)*, 2020, pp. 224–230.

[3] F. Ruggiero, V. Lippiello, and A. Ollero, "Aerial manipulation: A literature review," *IEEE Robotics and Automation Letters*, vol. 3, no. 3, pp. 1957–1964, 2018.

[4] E. Frachtenberg, "Practical drone delivery," *Computer*, vol. 52, no. 12, pp. 53–57, 2019.

[5] H. B. Khamseh, F. Janabi-Sharifi, and A. Abdessameud, "Aerial manipulation-a literature survey," *Robotics and Autonomous Systems*, vol. 107, pp. 221–235, 2018.

[6] P. E. I. Pounds, D. R. Bersak, and A. M. Dollar, "Practical aerial grasping of unstructured objects," in *2011 IEEE Conference on Technologies for Practical Robot Applications*, 2011, pp. 99–104.

[7] L. Y. Lee, O. A. Syadiqeen, C. P. Tan, and S. G. Nurzaman, "Closed-structure compliant gripper with morphologically optimized multi-material fingertips for aerial grasping," *IEEE Robotics and Automation Letters*, vol. 6, no. 2, pp. 887–894, 2021.

[8] D. Kim and P. Y. Oh, "Toward lab automation drones for micro-plate delivery in high throughput systems," in *2018 International Conference on Unmanned Aircraft Systems (ICUAS)*, 2018, pp. 279–284.

[9] U. A. Fiaz, M. Abdelkader, and J. S. Shamma, "An intelligent gripper design for autonomous aerial transport with passive magnetic grasping and dual-impulsive release," in *2018 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, 2018, pp. 1027–1032.

[10] M. Lieret, J. Lukas, M. Nikol, and J. Franke, "A lightweight, low-cost and self-diagnosing mechatronic jaw gripper for the aerial picking with unmanned aerial vehicles," *Procedia Manufacturing*, vol. 51, pp. 424–430, 2020.

[11] D. Rus and M. T. Tolley, "Design, fabrication and control of soft robots," *Nature*, vol. 521, no. 7553, pp. 467–475, 2015.

[12] J. Fishman, S. Ubellacker, N. Hughes, and L. Carlone, "Dynamic grasping with a "soft" drone: From theory to practice," in *2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2021, pp. 4214–4221.

[13] Y. Yang, K. Jin, H. Zhu, G. Song, H. Lu, and L. Kang, "A 3d-printed fin ray effect inspired soft robotic gripper with force feedback," *Micromachines*, vol. 12, no. 10, p. 1141, 2021.

[14] M. Ng, F. Vanegas, K. Morton, J. Sandino, and F. Gonzalez, "Design and flight test of an aerial manipulator for applications in gps-denied environments," in *2022 International Conference on Unmanned Aircraft Systems (ICUAS)*, 2022, pp. 20–29.

[15] R. Cano, C. Pérez, F. Pruano, A. Ollero, and G. Heredia, "Mechanical design of a 6-dof aerial manipulator for assembling bar structures using uavs," in *2nd RED-UAS 2013 workshop on research, education and development of unmanned aerial systems*, vol. 218, 2013.

[16] M. Xu, T. Senoo, and T. Takaki, "An underactuated parallel-link gripper for a multicopter capable of plane perching," *ROBOMECH Journal*, vol. 9, no. 1, pp. 1–12, 2022.

[17] M. E. Mumcuoğlu, I. Yüksel, and E. Altuğ, "Design of an automatic item pick-up system for unmanned aerial vehicles." *Celal Bayar University Journal of Science*, vol. 16, no. 1, 2020.

[18] D. Kim and P. Y. Oh, "Lab automation drones for mobile manipulation in high throughput systems," in *2018 IEEE International Conference on Consumer Electronics (ICCE)*, 2018, pp. 1–5.

[19] T. W. Danko, K. P. Chaney, and P. Y. Oh, "A parallel manipulator for mobile manipulating uavs," in *2015 IEEE international conference on technologies for practical robot applications (TePRA)*. IEEE, 2015, pp. 1–6.

[20] H. Lee and Y. Choi, "Stackable 4-bar mechanisms and their robotic applications," in *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2010, pp. 2792–2797.

[21] D. Saha, S. Sanfui, R. Kabiraj, and S. Das, "Design and implementation of a 4-bar linkage gripper," *IOSR Journal of Mechanical and Civil Engineering*, vol. 11, pp. 61–66, 09 2014.

[22] COEX, "Autonomous flight," Nov. 2022, [Online]. Available: https://clover.coex.tech/en/simple_offboard.html#autonomous-flight. [Online]. Available: https://clover.coex.tech/en/simple_offboard.html#autonomous-flight

[23] PX4, "Auto-tuning," Nov. 2022, [Online]. Available: https://docs.px4.io/main/en/config/autotune.html.

[24] B.-C. Min, J.-H. Hong, and E. T. Matson, "Adaptive robust control (arc) for an altitude control of a quadrotor type uav carrying an unknown payloads," in *2011 11th International Conference on Control, Automation and Systems*, 2011, pp. 1147–1151.

[25] P. E. I. Pounds, D. R. Bersak, and A. M. Dollar, "Practical aerial grasping of unstructured objects," in *2011 IEEE Conference on Technologies for Practical Robot Applications*, 2011, pp. 99–104.

[26] X. Kan, J. Thomas, H. Teng, H. G. Tanner, V. Kumar, and K. Karydis, "Analysis of ground effect for small-scale uavs in forward flight," *IEEE Robotics and Automation Letters*, vol. 4, no. 4, pp. 3860–3867, 2019.

[27] J.-W. Lee, N. Xuan-Mung, N. P. Nguyen, and S. K. Hong, "Adaptive altitude flight control of quadcopter under ground effect and time-varying load: theory and experiments," *Journal of Vibration and Control*, p. 10775463211050169, 2021.

[28] S. Smith and Y.-J. Pan, "Observer-based super-twisting sliding mode control of quadcopters," in *Proceedings of the 2022 CSME International Congress of Canadian Mechanical Engineering*, vol. 5, 2022.