Hybrid VTOL UAV Autonomous Operations from Mobile Landing Pad

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***Abstract*—Flight missions carried out from mobile landing pads are a challenge for hybrid VTOL UAVs. An approach to precise landing on a moving pad requires implementing an appropriate control system supported by accurate relative positioning. The paper presents the results of real conditions test on such a UAV system, which is a combination of hybrid VTOL UAV and dedicated landing pad navigation station that was developed to allow UAVS to take off and land on a mobile platform. Tests were carried out by employing a mobile landing platform mounted on a trailer pulled by a car. During the tests, the hybrid VTOL UAV was able to take off and land on the landing platform moving at a speed up to 25 km/h, and all flight trials ended with success. These tests improved the UAV system before the final test on maritime conditions.**

***Index Terms*—hybrid VTOL UAV, autonomous vertical landing and take off, mobile landing platform, position tracking**

I. INTRODUCTION

Performing autonomous flight missions from a mobile landing pad would be a highly expected feature of UAV systems in cases when there is no possibility or time to set a stationary landing pad or create a runway [1]. Applications, in which this feature could be applied, start from military reconnaissance missions from combat vehicles and end at search and rescue missions from the vessel's deck [2]. Despite various applications where mobile landing pads could be used, the major problem to be solved remains the same i.e. how to monitor the relative position and speed between the UAV and the landing pad, and how to control the landing approach so that it is performed at the center of the landing pad of a limited size. Moreover, if we include wind gusts and vortexes around the landing pad and airflow caused by the landing pad movement, the problem becomes challenging, especially if the UAV has wing-like hybrid VTOLs. Vehicles of This kind are more sensitive to weather conditions and achieving a safe landing on a mobile platform requires accurate calibration of control loops and positioning system which tracks the landing pad in the landing phase. Most of the well-known research on the problem of taking off and landing on mobile landing pads concerns simulations studies and these involving holonomic vehicles like multicopper [3], [4]. Some of those tests employ a special platform in which movement is emulated [5], [6] or done manually [7]. Whereas in the work [8], the landing pad is placed on the mobile vehicle and moves along a straight line in indoor condition at a low speed. Interesting research on the discussed problem is presented in [9], where a landing platform mounted on the roof of a car is moving at a speed of 14 m/s, giving satisfactory results. However, the most meaningful results can be found in [14], where experiments with an UAV with tilting engines nacelles are carried out in both inland with the use of a car trailer and maritime conditions on the ship's deck at a speed of 18 km/h. Those results present flight phases such as taking off, hovering 25 meters above the pad level, and landing without flying away at a significant distance. Landing on a mobile landing platform during its movement must be supported by a precise relative positioning system. It cannot be based on a standard GNSS system due to the limited accuracy. The use of RTK (real-time kinematic) GNSS becomes essential and obligatory to achieve accurate positioning UAVs with respect to the landing pad. But it requires additional stationary reference base station [10], [14] or the usage of RTK paid services and internet link [11]. In many applications there is no possibility to utilize the RTK GPS system, thus some alternate methods should be found. UWB (Ultra-Wide Band) technology is promising, and it can improve the accuracy of positioning especially in the areas where there are problems with GPS signal strength, and it can be used with UAV systems [12], [13]. The disadvantage of UWB technology can be the installation of additional radio equipment around the landing pad and on masts with different heights and effectiveness limited to several meters. The paper presents results from the research conducted by experimental trials of a hybrid VTOL UAV in real-world conditions. The aim of the research is to observe the stability of a takeoff and the precision of landing on the pad having 6x6 meters dimensions, mounted on a trailer and pulled by a car on the ground road in the old military zone to secure the safety of the flights. The maximum achieved speed of the landing pad was 25 km/h. The paper presents the experimental VTOL

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platform, its onboard systems' architecture, descriptions of performed flight missions, assumed flight parameters and achieved results.

II. The VTOL UAV platform

The VTOL UAV platform (presented in the Fig. 1) used in the studies is a flying robot equipped with a vertical takeoff and landing function, which, in combination with an intelligent navigation and obstacle avoidance system, provides multitasking and wide applications such as: patrolling and monitoring of vast areas (forests, deserts, country borders, land and water transport routes), supervision of large events, transport and precise delivery of cargo, large-area aero photogrammetry for precision agriculture, etc. The VTOL UAV is a hybrid unmanned aerial vehicle being a combination of a fixed wing airframe and a four-rotor rotorcraft - quadrotor. This combination gives the fixed wing platform the possiblity to a vertical takeoff and landing, what sgnificantly extends the application area and gives new interesting research areas in control of that kind of system dynamics. The fixed wing airframe is made of carbon-kevlar composite and is equipped with H-tail. Dimensions of the platform are 3 meters wide, 1.7 meters long. The maximum takeoff weight (MTOW) of the VTOL UAV is 20kg. The VTOL UAV is equipped with a pusher type electric motor mounted on the rear of the fuselage (for forward marching and fixed wing operation mode) and 4 electric motors installed on two extended tail booms to ensure the vertical takeoff and landing function (for multicopter mode and multicopter flight operations). The VTOL UAV on-board equipment represents:

- autopilot allowing automatic flight control and the implementation of the function of switching from/to airplane mode to/from helicopter mode, following the mobile landing platform (ferry, ship, mobile robot), precise automatic landing on a mobile landing platform,
- vision computer responsible for image processing related to precise landing and airstrip monitoring to perform the collision avoidance function.

The basic flight performance of VTOL UAV are as follows:

- the maximum level flight velocity - 30 m/s (on a forward marching pusher motor in horizontal flight in fixed wing mode, depending on the size of the propeller used, atmospheric conditions etc.),
- the minimum level flight velocity - 14 m/s (in fixed wing mode),
- flight range - about 100 km (depending on the capacity of the power pack, atmospheric conditions and the type of the takeoff phase - multicopter or fixed wing),
- maximum flight time - up to 2 hours (depending on the weight, flight scenario, takeoff conditions and mode, flight conditions).

III. VTOL's system architecture

The system consists of two main subsystems. First of them is the VTOL UAV subsystem. It is divided into two functional parts: autopilot and onboard computer. The autopilot (Cube hardware) operates the PX4 software incorporating the custom implementation of 'follow me' flight mode with optimised PID controller. It is responsible for navigation and position tracking. It directly controls actuators and reads sensor data. The standard telemetry port (USART hardware layer) is used to communicate with the onboard computer (x64 architecture, linux OS driven with ROS - Robotic Operating System software). The computers' main functionality is the estimation of the landing pad position and the velocity when the radio link is down. The state of the landing pad is calculated using the Kalman filter. Its second task is the commandment on the flight phases and autopilot's flight modes. It also serves as the communication routing device as it works as a link between the autopilot and the ground station. The VTOL UAV subsystem schematic is presented in the Fig.2. The ROS software on the VTOL's onboard computer is capable of blending the additional data from local navigation systems into the position estimation module. The potentially available sources of information are vision processing and image analysis systems or radio beacons (both of these were tested only in the static trials).

Fig. 1. The VTOL UAV used in the studies.

The second subsystem is Ground Station. It is controlled by the embedded computer (x86 Windows OS). The device uses two different and separated GNSS modules (primary and secondary) and magnetometer to determine the landing pad position and heading with the sub-meter accuracy. The distance between the GNSS antennas was created to do the independent heading calculation based on their relative positions. This ensures additional redundancy in high magnetic disruptions environments like shipdecks or heavy vehicles. It receives the telemetry from the UAV and sends back the tracking parameters (PID coefficients, position offsets, etc.) and mission commands (take of, land, mission waypoints data, etc.). It is connected with the user terminal with the wi-fi network. The schematic of the Ground Station is presented in the Fig. 3.

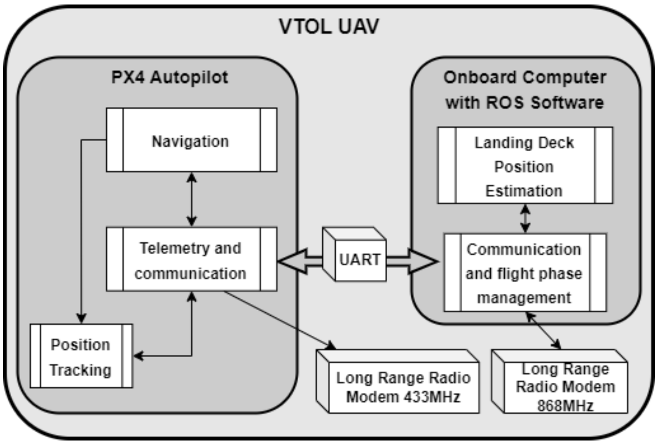

Fig. 2. VTOL UAV subsystem schematic.

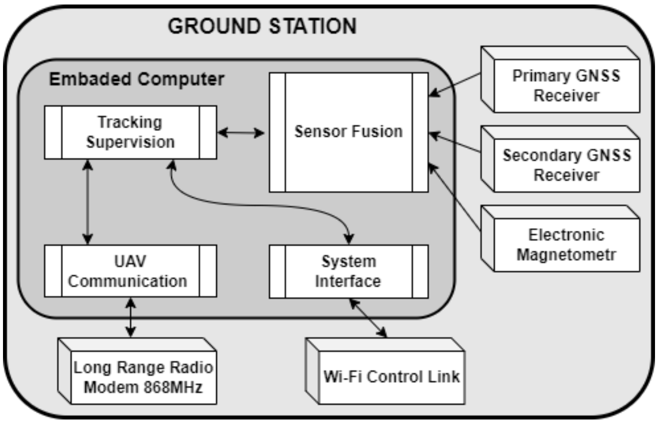

Fig. 3. Ground Station subsystem schematic.

The system in test configuration is operated by up to three users. The mission commander (obligatory) is responsible for tracking system initialisation (parameters configuration for test conditions), starting a mission and giving permissions for flight mode transitions. The supervisor officer and emergency pilot are optional staff. They are responsible for system health monitoring and taking over manual control in emergency situation. The system might by operated fully autonomously. The test configuration is showed in the Fig. 4.

IV. Experimental Tests

The main purpose of the flight tests was to verify and carefully check the full mission of VTOL UAV in both MC (MultiCopter) and FW (Fixed-Wing) modes and transitions from MC to FW and from FW to MC modes. The full mission consisted of the following flight phases: 1) automatic, vertical takeoff from the mobile landing pad, 2) following the mobile landing pad in MC mode, 3) automatic transition to FW mode, 4) flight in FW mode to a desired waypoint, 5) return to the current position of the mobile landing pad, 6) automatic transition to the MC mode, 7) re-following of the mobile landing pad in MC mode, 8) vertical automatic landing on

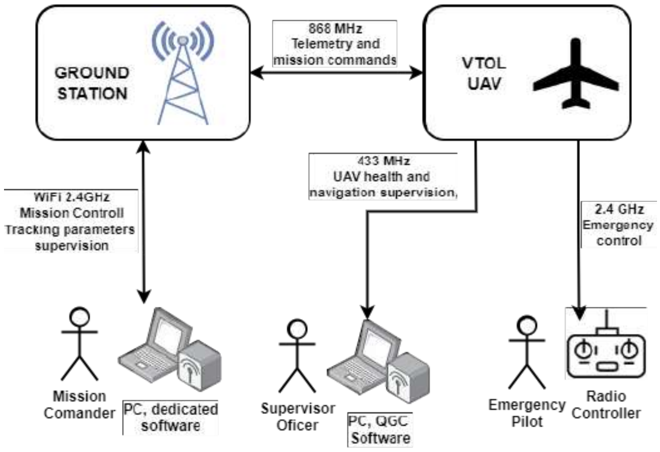

Fig. 4. Overall system schematic in test configuration.

mobile platform. Experimental tests were carried out in the restricted area of the old military compound located nearby the village - Czerwony Bór. The area is a part of the National Forests complex. The localization is of a sufficient range of sight of about one kilometer and a prominent level of safety of the tests in the case of a UAV failures. In-flight tests were performed under the following weather conditions:

- temperature: 30 °C,
- relative wind speed: 4-5 m/s,
- wind gusts: 9-13 m/s,
- cloud cover: 60 %,
- humidity: 50 %.

Few autonomous flight missions were performed during the tests from the mobile landing pad mounted on a trailer pulled by the van car (Fig. 5). The mobile landing pad was prepared on a tow truck. The dimensions of the landing pad are 5 meters wide and 5 meters long. All of the flights were performed at an altitude of 50 meters. The speed of the van car with the tow truck was about 25 km/h. The recurrence of the landing and the operational reliability of all system components were checked. Fig. 6 presents several frames of the films from an exemplary flight test recorded by a separate multicopter and a VTOL on-board camera.

V. Results

The results obtained during one exemplary in-flight test are presented in Figs. 7 - 14. Fig. 7 presents Roll, Pitch and Yaw orientation angles of VTOL UAV during one whole mission flight. It can be noticed here that after the transition from FW to MC mode in the time interval 500-520s there were large oscillations and changes in the Roll and Pitch angles. Initially, descending process of VTOL and wind gusts were suspected to be the reason of such behavior. These types of flying platforms (hybrid combination of fixed wind and multicopter) are particularly sensitive to disturbances caused by wind gusts. It is due to the large wings surface. What is more, decreasing the altitude requires a reduction in the rotational speed of the propellers of the four motors responsible for vertical

Fig. 5. The VTOL UAV on the mobile landing platform before the start of the tests.

Fig. 6. The flight of VTOL UAV. Starting from top: takeoff from moving landing pad, flight in airplane mode, landing on the moving landing pad

takeoff and landing phases. Further analysis of the logged data revealed a different cause of that dangerous situation (it will be explained later). Despite the potential danger, the VTOL control system was able to keep the UAV in stability region. It can also be seen that the Yaw angle is correctly maintained in line with the motion direction of the moving landing pad. Fig 8 shows the air speed. The instantaneous speed in relation to the air just after the transition was over 25 m/s in the FW mode. Fig 9 shows the flight altitude profile of the UAV, which was 50 meters with some fluctuations due to the different phases of the mission being performed. There is a slight decrease in altitude in 440 seconds of flight just after switching from MC to FW mode. Fig 10 shows the trajectory of the UAV during the execution of the mission. The waypoint to which the UAV was heading was marked. Additionally, the takeoff and landing points as well as the trajectory of the mobile landing site are marked. The total distance during the test mission performed by the UAV was about 1.5 km. The average speed during the mission in MC mode was around 11.1 km/h, the average speed in FW mode was around 80.1 km/h. In the Fig. 11 and Fig. 12 control signals in MC mode and FW mode were presented respectively for roll, pitch, yaw control channels. What is more, the total thrust was also presented on these plots. It is easy to notice that in the MC mode in the time range of 500-520s, VTOL motors are working in saturation. This is due to the excessive roll and pitch oscillations. In the case of the FW mode, motor control signal saturation appears only for a short time during the transition from MC to FW in order to gain speed as quickly as possible and create sufficient lift force of wing to be able to turn off the 4 motors for MC mode. Fig. 13 and Fig. 14 presents the linear velocities during VTOL mission in FW mode and MC mode (after transition from FW mode). In Fig. 14 activation signal of a following landing pad/target function was marked. It can be seen that when this following function was activated, the speed setpoints in the x and y axes jumped suddenly to large values (about -10 m/s). It caused high oscillations between 500 and 520 seconds of flight, noticeable on the roll and pitch angles. The reason were the errors in the implementation of the control system. Thanks to the tests, they were precisely detected and corrected.

VI. Conclusions

The results from the experimental flight missions of the hybrid VTOL UAV performed from a mobile landing pad present new possibilities for such kind of drones, through the usage in applications in the areas where stationary landing pads cannot be used, for example in long-range flights essential in search, rescue or surveillance missions. The maximal speed of the car pulling the tow truck with the landing pad was 25 km/h which could be equivalent to the operational speed of many vessels and military armored vehicles. Launching hybrid VTOL UAV from vessels or military armored vehicles and then performing a few kilometers range flight would be a significant improvement in UAV possibilities, especially as it was proved, it can land back in a safe way with a high accuracy. In the experiments the range of flights was limited

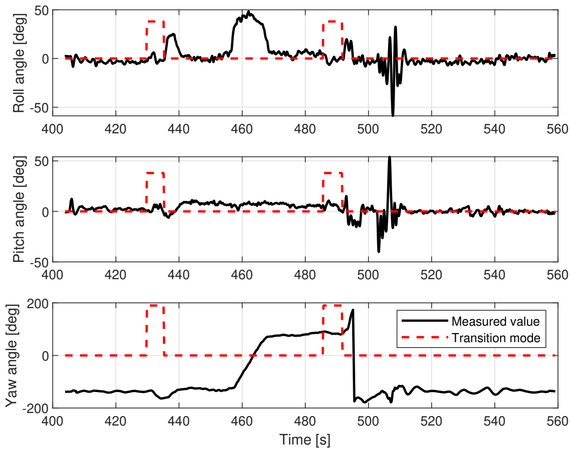

Fig. 7. VTOL roll, pitch and yaw angles during in-flight test.

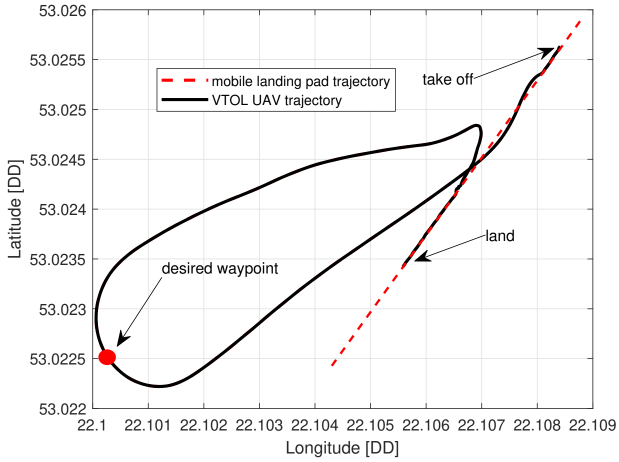

Fig. 10. VTOL path during in-flight test.

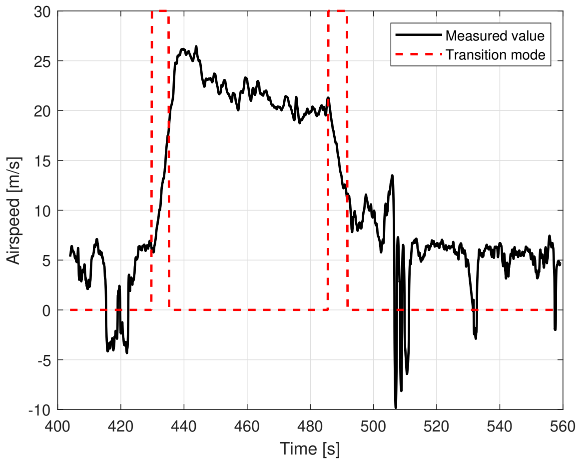

Fig. 8. VTOL airspeed during in-flight test.

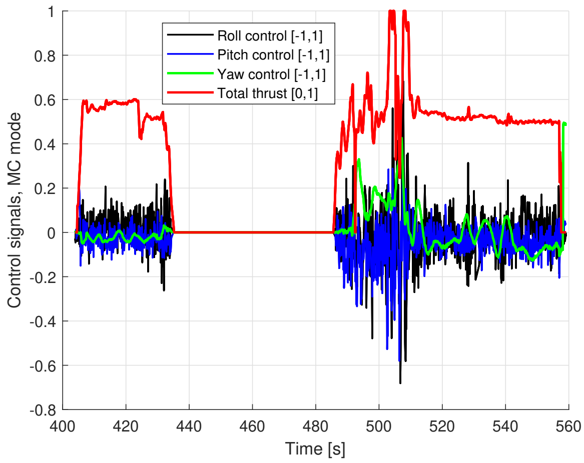

Fig. 11. VTOL control signals in MC mode.

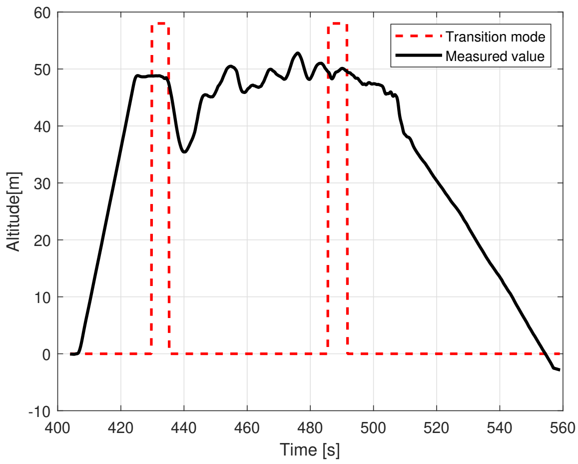

Fig. 9. VTOL altitude during in-flight test.

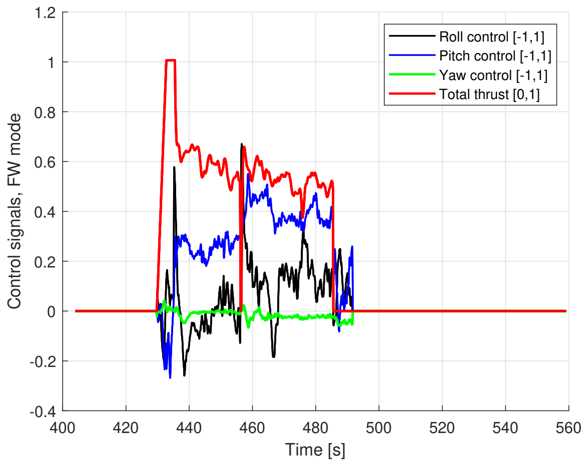

Fig. 12. VTOL control signals in FW mode.

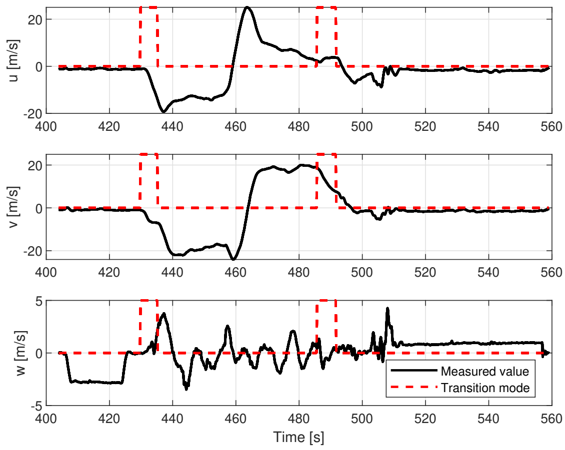

Fig. 13. Linear speeds ov VTOL during mission.

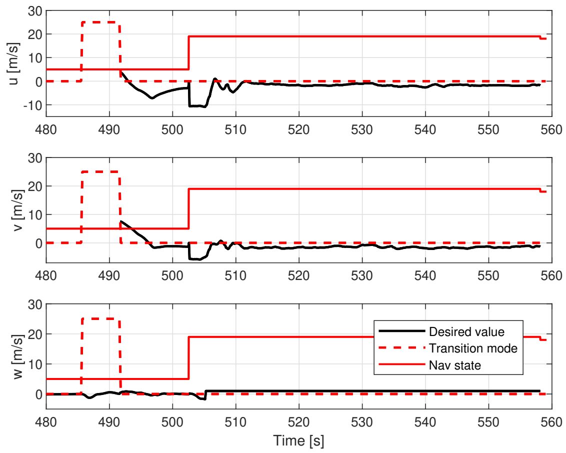

Fig. 14. Desired linear speeds in MC mode after transition from FW to MC.

to the line of sight (LOS) due to safety requirements with the usage of a UAV above 10 kg of weight. Our hybrid VTOL UAV flew away at about 700-800 meters from the landing platform. It is quite a short distance because the maximal available flight range is about 100 km, assuming a mission would last 2 hours at an airspeed of 100 km/h. But such BLOS (beyond line-of-sight) flights are under restrictions. Therefore, even in the place where our experiments were conducted, BLOS could not be performed without accurate permissions form the government organisations. Concluding, the experiments show that present UAV technology makes it possible to achieve a fully autonomous flight mission from a mobile landing platform with the use of hybrid VTOL UAV. The results were verified in the next stage of the research i.e. in maritime conditions during a cruise of a commercial ferry ”Wolin” [15].

REFERENCES

[1] Koo, Soyeon and Kim, Seungkeun and Suk, Jinyoung and Kim, Youdan and Shin, Jongho,”Improvement of Shipboard Landing Performance of Fixed-wing UAV Using Model Predictive Control”,International Journal of Control, Automation and Systems, Vol. 16, No 10, pp.2697–2708, 2018,

[2] Feng, Y., Zhang, C., Baek, S., Rawashdeh, S., and Mohammadi, A. (2018). Autonomous landing of a uav on a moving platform using model predictive control. Drones, 2:34,

[3] Acuna, R., Zhang, D., and Willert, V. (2018). Vision-based uav landing on a moving platform in gps denied environments using motion prediction. In 2018 Latin American Robotic Symposium, 2018 Brazilian Symposium on Robotics (SBR) and 2018 Workshop on Robotics in Education (WRE), pages 515–521,

[4] Polvara, R., Sharma, S., Wan, J., Manning, A., and Sutton, R. (2017). Towards autonomous landing on a moving vessel through fiducial markers. In 2017 European Conference on Mobile Robots (ECMR), pages 1–6,

[5] Wang, L. and Bai, X. (2018). Quadrotor autonomous approaching and landing on a vessel deck. Journal of Intelligent & Robotic Systems, 92:125–143,

[6] Sanchez-Lopez, J., Pestana, J., Saripalli, S., and Campoy, P. (2014). An approach toward visual autonomous ship board landing of a vtol uav. Journal of Intelligent & Robotic Systems: Theory and Applications, 74(1-2):113–127,

[7] Ling, K., Chow, D., Das, A., and Waslander, S. L. (2014). Autonomous maritime landings for low-cost vtol aerial vehicles. In 2014 Canadian Conference on Computer and Robot Vision, pages 32–39,

[8] Falanga, D., Zanchettin, A., Simovic, A., Delmerico, J., and Scaramuzza, D. (2017).Vision-based autonomous quadrotor landing on a moving platform. In 2017 IEEE International Symposium on Safety, Security and Rescue Robotics (SSRR),

[9] Borowczyk, A., Tien, N., Nguyen, A., Nguyen, D., Saussie, D., and Le Ny, J. (2017). Autonomous landing of a quadcopter on a high-speed ground vehicle. Journal of Guidance, Control, and Dynamics, 40:1–8,

[10] Marcon, P., Janousek, J., and Kadlec, R. (2018). Vision-based and differential global positioning system to ensure precise autonomous landing of uavs. In 2018 Progress in Electromagnetics Research Symposium (PIERS-Toyama), pages 542–546,

[11] Grekhov, A., Kondratiuk, V., and Ilnytska, S. (2020). Rpas communication channels based on wcdma 3gpp standard. Aviation, 24(1):42–49,

[12] Cisek, K., Zolich, A., Klausen, K., and Johansen, T. A. (2017). Ultrawide band real time location systems: Practical implementation and uav performance evaluation. In 2017 Workshop on Research, Education and Development of Unmanned Aerial Systems (RED-UAS), pages 204–209,

[13] You, W., Li, F., Liao, L., and Huang, M. (2020). Data fusion of uwb and imu based on unscented kalman filter for indoor localization of quadrotor uav. IEEE Access, 8:64971–64981,

[14] Kang, Y., Park, B.-J., Cho, A., Yoo, C.-S., Kim, Y., Choi, S., Koo, S.-O., and Oh, S. (2018). A precision landing test on motion platform and shipboard of a tilt-rotor uav based on rtk-gnss. International Journal of Aeronautical and Space Sciences, 19(4):994–1005.

[15] Ambroziak, L., Ciezkowski, M., Wolniakowski, A., Romaniuk, S., Bożko, A., Ołdziej, D., & Kownacki, C. (2021). Experimental tests of hybrid VTOL unmanned aerial vehicle designed for surveillance missions and operations in maritime conditions from ship-based helipads. Journal of Field Robotics, 1– 15, https://doi.org/10.1002/rob.22046.