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Vertical Take-Off and Landing fixed-wing designed for autonomous missions

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Abstract— **This paper presents the design and development of a Vertical Take-off and Landing (VTOL) fixed-wing aircraft intended for autonomous missions. It provides an overview of the current state of VTOL technology and its applications. The paper focuses on fixed-wing VTOL aircraft created by Academic Scientific Association High Flyers from the Silesian University of Technology in Poland. The design process and considerations are discussed in detail, including aerodynamics, selection of materials, hardware, control systems and software. Finally, the paper discusses real-world scenarios that the designed UAV could be used to solve real-world problems, such as targeted plant protection or the deployment of oral vaccines for wildlife. The authors successfully tested solutions presented in the paper during competitions and real practical applications. Overall, this paper provides a comprehensive look into the design and development of a VTOL aircraft for autonomous missions and presents its effectiveness and capabilities in solving real-life problems.**

I. INTRODUCTION

Vertical Take-off and Landing technology (VTOL) is a field of great interest in the unmanned aerial vehicle (UAV) industry. The main advantage of a fixed-wing VTOL over conventional aircraft is the combination of high-speed and long-distance flight with precise vertical take-off and landing. Fixed-wing VTOL UAVs can find a use for a variety of applications in various industries, including high-resolution photography, agriculture [1], controlling borders and water environments, ISR (intelligence, surveillance, reconnaissance) missions [2] or object detection and recognition [3]. The development of fixed-wing VTOL has been ongoing for a few decades [4]. Although they were all initially manned, they still significantly impacted later UAV models. Technology has evolved in recent years. UAV technology is shifting towards VTOL due to its ability to land in many locations, resulting in higher suitability for operations in urban areas. VTOLs do not require extended runway space, offering advances over multirotors (mostly extended flight duration). Due to the high technological advancement, more and more VTOL UAVs are being developed, such as HQ-60 or GL-10, by NASA [5]. There are several types of VTOL aircraft, including Tilting Ducted Fan[6], Tilt Wing [7], Tilt rotor [8] [9], Gyrodyne [10], and Thrust Vector Controlled VTOL [11].

This paper introduces the most popular applications using fixed-wing VTOL UAVs. It will focus on a comprehensive look at the tilt-rotor VTOL UAV constructed by the Academic Scientific Association High Flyers from the Silesian University of Technology in Poland. The paper will provide an overview of the design process, where special consideration was given to autonomous mission capabilities. It will include the aerodynamic and structural design, propulsion system, control system (focused on VTOL's transition), and used hardware and software. It will also present the most important parameters of the created UAV with the CFD (Computational Fluid Dynamics) analysis to evaluate the performance and stability of the aircraft. The custom VTOL UAV will be presented as a part of robust autonomous systems which solve real-world problems primarily related to agriculture, disease prevention and emergency services. The developed solutions will be thoroughly described and demonstrate the VTOL UAV's capabilities and the potential for similar applications.

II. VTOL APPLICATIONS

VTOL fixed-wing aircraft can have various applications in areas where proper runways cannot be provided, and the requirement for a long-range flight capability exists. Some of the most notable applications of VTOLs include:

- Agriculture: The VTOL UAV is significantly suited for precision agriculture [12], where it can cover extensive farmlands. Onboard sensors can collect data about crop health and soil moisture that one can use to optimize crop yields by reducing water and fertilizers.
- Surveillance: The VTOL UAV can be used to monitor a country's borders and coasts and monitor road traffic accidents. Furthermore, UAVs in maritime sectors [13], equipped with high-resolution PTZ (Pan-Tilt-Zoom) cameras, are helpful in the detection of smuggling and poaching activity.
- Delivery: The VTOL UAV with dedicated cargo space can be used for efficient delivery to remote and hard-to-reach areas. For example, VTOLs can deliver medical supplies, food, and other necessities to disaster-stricken areas. Additionally, they can also quickly transport blood or organs for transplantation to hospitals.
- Emergency Services: The VTOL UAV can be used by emergency services to operate in inaccessible places. For example, UAVs can help in search and rescue missions in challenging terrains, such as mountains, forests, or water reservoirs.

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III. HF-10 SZCZYGIEŁ DESIGN

The following section will discuss the design and construction of the VTOL UAV developed by the High Flyers team. The created UAV was named HF-10 SZCZYGIEŁ. It was designed with a particular emphasis on autonomous mission capabilities. It is presented in Fig. 1, and its specifications are shown in Table I.

TABLE I
HF-10 VTOL AIRCRAFT SPECIFICATION

Parameter	Value
Minimum horizontal speed	10 [m/s]
Cruising speed	19-21 [m/s]
Maximum speed	30 [m/s]
Flight time	105 [min]
Range performance	126 [km]
Wing area	64.8 [dm^2]
Wing span	2880 [mm]
Length	1600 [mm]
Propeller diameter and pitch	16x8 [inch]
Maximum Take-off Weight (MTOW)	8 [kg]

Fig. 1. HF-10 SZCZYGIEŁ VTOL made by High Flyers team

A. Control strategy

From the point of view of control theory, a VTOL aircraft is a highly non-linear and non-stationary system. The control problem should be considered as a multidimensional issue, where the number of control channels depends on the current flight mode. Three flight modes were distinguished. First one is multirotor mode that is used during hover, takeoff, and landing. Second one is high-effeciency fixed-wing mode that is suitable for long-range horizontal flight. The last one is transient mode in which the UAV is transitioning from multirotor mode to fixed-wing mode or vice versa Fig. 2. Multirotor and fixed-wing control methods are well known and described in the literature [14], [15], [16]. Difficulties may arise in the transition mode, in which the front motors are tilting, changing direction of thrust and pulling aircraft forward. During this phase, the airflow around the wings becomes turbulent.

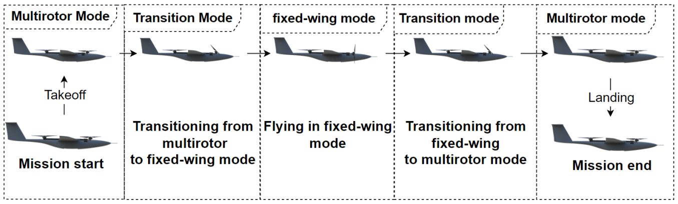

Fig. 2. Transition from different flight modes during a mission

Due to the non-linearity and non-stationarity of the control object, this flight phase is demanding in terms of control system reliability. Here, the results of the CFD analysis, presented in Paragraph III-C, are significant, as they are a source of knowledge about the aerodynamic properties of the aircraft.

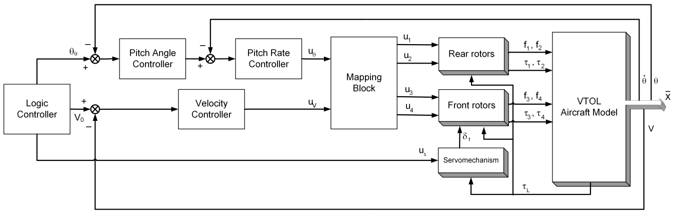

Fig. 3. Structure of the control system in transition mode

Taking the above into account, the following structure of the control system was proposed (Fig. 3). The logic controller, operating sequentially in individual time intervals, controls the tilt angle of the nacelles and simultaneously generates the set values for the other two control channels. A cascade structure was used to control the pitch angle, while a classic system with a PID controller was applied for velocity control. Finally, the allocation of thrust to individual rotors occurs in the mapping block. The parameters of individual controllers were tuned by the method of closing subsequent loops based on root locus analysis, on the principle of multi-stage rapid prototyping, initially in off-line SITL (software in the loop) simulations, then in the HITL (hardware in the loop) structure, and finally in flight.

B. VTOL flight dynamics model

Effective control of the platform in individual flight modes is carried out through appropriate subsets of the following control quantities:

$$\bar{U} = [u_1, u_2, u_3, u_4, u_s, u_H, u_K, u_L]^T \tag{1}$$

where: u_i – PWM (Pulse-Width Modulation) motor inputs (i=1,…,4), u_s – control signal of the tilting servo, u_H – control signal of the elevator, u_K – control signal of the rudder, u_L – control signal of the ailerons.

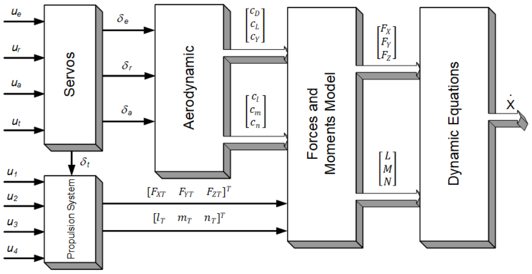

Fig. 4. Model of VTOL flight dynamics

In Fig. 4, a block diagram of the dynamics model of the designed VTOL aircraft is presented. The model includes the rigid body dynamics equations, the equations of forces and moments, and its aerodynamics, which change depending on the current flight mode. In addition, the aircraft has typical aerodynamic surfaces such as ailerons, elevator, and rudder. The propulsion system consists of four brushless motors arranged symmetrically relative to the aircraft's longitudinal axis. Two motors are located behind the left and right wings trailing edges, and the other two are in front of the wing's leading edge. Two front engines, mounted on movable nacelles, are tilted synchronously towards the horizontal direction, allowing the UAV to accelerate forward.

C. CFD simulation

The VTOL platform was investigated with the help of Computational Fluid Dynamics (CFD) simulations. Since the complete characteristics of the VTOL had to be determined, the non-symmetrical interactions were analyzed. Therefore, the computational domain consisted of the full geometrical model without using the symmetry plane. It, in turn, led to a significant number of mesh elements. The domain had the shape of a paraboloid of revolution spanning from -20 m to +30 m in the platform's longitudinal direction. The radius of the outlet surface was equal to 30 m. Since the platform design was based on non-uniform rational basis splines, the unstructured mesh and the prism inflation layer were used. Based on the grid-independence study, the 16 million elements mesh with 15 laminar sublayers was chosen as the optimal solution. The average orthogonal quality of used mesh was equal to 0.876. The simulations were performed using a pressure-based steady-state solver. The Langtry-Menter four-equation Transitional SST turbulence model was used. In this model, the transport equations are coupled with the intermittency equation and the equation for the transition onset criteria in terms of momentum-thickness Reynolds number. The Semi-Implicit Method for Pressure Linked Equations (SIMPLE) was used for pressure-velocity coupling. All discretization schemes were set to the second order up-wind, whereas the gradients were calculated using Green-Gauss Node-Based method. The boundary conditions were defined as follows: the paraboloid peripheral was set as velocity inlet described by direction vector and velocity magnitude, the back surface was set as pressure outlet, and the surface of the UAV was set as a wall with the no-slip condition. In Fig. 5, the lift and drag coefficients for Reynolds number equal to 237 000 are presented. It may be noticed that the lift becomes negative below -1°angle of attack, and the stall appears at 12°angle of attack. Although one may find scientific reports in which designs of higher aerodynamic efficiency are presented; still the obtained results are, in our opinion, satisfactory.

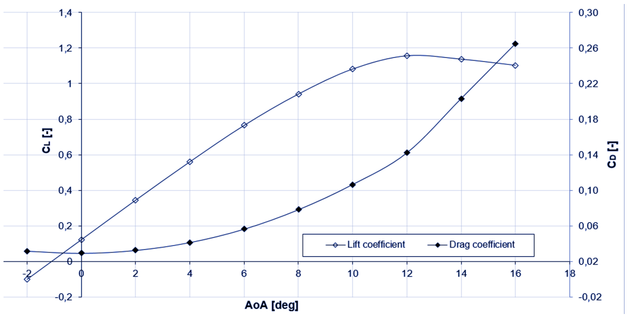

Fig. 5. Lift and drag coefficients for Re = 237 000

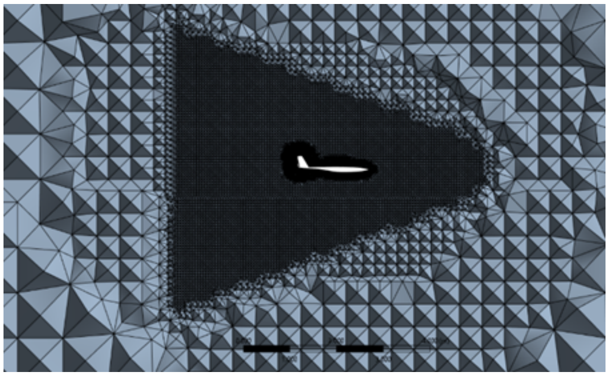

Fig. 6. General view of the mesh and orthogonal quality graph.

D. Mechanical design

The VTOL UAV's body is made of a carbon fiber composite. The wing structure consists of balsa wood ribs and open-cell foam reinforcements, while the hull has hollow construction. The tilt mechanisms are made of aluminum and are optimized for weight reduction and rigidity. The lift from the wings and tail horizontal stabilizer is transferred to the hull through carbon fiber struts. This design decision allows for detaching the wings and tail stabilizers for transport. It is possible due to the use of special connectors that allows the wing power circuitry to disengage from the aircraft's body.

E. Design for expansion

The possibility of expansion was heavily considered from the beginning of the development process. The UAV's fuselage can accommodate multiple modules, dependent on mission requirements.

The principal place for mission-specific modifications is VTOL UAV's payload bay (Fig. 7), which can hold deployable loads, special accessories such as cameras or sensors, as well as additional flight computers enhancing the platform's mission characteristics. The bay walls have four retractable pins, allowing for mounting and automatically dropping various payloads. In addition, the payload bay's top side is outfitted with mounting holes and electric connectors to install equipment such as cameras and flight computers.

Another part of the fuselage allowing for mission-specific changes is the nose of the aircraft, which can be swapped or modified to accommodate additional cameras or sensors. The whole assembly can be easily unmounted and interchanged, allowing for a fast turnaround between missions.

F. Hardware and software

The selection of appropriate software and hardware components is crucial in designing a VTOL aircraft for autonomous missions. Fig. 8 presents the general concept and connections between components. The critical component

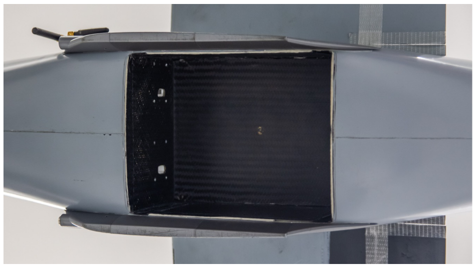

Fig. 7. HF-10 SZCZYGIEŁ VTOL payload bay

is a PX4 autopilot which runs on Pixhawk hardware. The PX4 is an open-source flight control software widely used in the UAV industry and is considered the most reliable yet flexible solution among other options. It provides a powerful and flexible framework for controlling and navigating the aircraft. It also allows for the integration of various sensors and peripherals and provides a uniform way of controlling and navigating the platform regardless of its current flight mode.

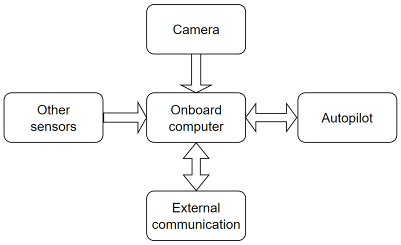

Fig. 8. Hardware and connections onboard VTOL platform

NVIDIA Jetson Xavier NX was used as an onboard computer. It is equipped with a powerful NVIDIA GPU, which can be used for processing the video stream using artificial intelligence and computer vision algorithms that can be crucial for autonomous missions. It provides high performance with low power consumption. External communication is provided by IEEE 802.11ah long-range radio module, which is used to send telemetry data and video streams.

ROS (Robot Operating System) was used as a core software for autonomous operation. ROS is a framework consisting of libraries and tools dedicated to developing robotic applications. It provides a modular architecture and unified communication interface. For that reason, it allows for easy integration of various modules. Numerous pre-existing packages for sensor support, communication, and common tasks such as path planning and offboard control also accelerate development. Furthermore, it allows simulation of the prepared system using the Gazebo simulator and evaluation of the system's performance in a safe and controlled environment.

Software structure (Fig. 9) is mainly built with the ROS programming platform. The ROS and mission control software run on the onboard computer. MAVROS is a ROS package that connects software inside the mission control module and VTOL PX4 autopilot using the MAVlink protocol. Thanks to the integration of PX4 with ROS and the Gazebo simulator, the complete software solution can be run in simulation. The mission control module is a state machine responsible for integrating the system, taking the mission plan and image processing input to calculate the trajectory in different phases of the mission. The generated trajectory is then processed by MAVROS and forwarded to PX4. Furthermore, the system structure allows for stable external connection to the ground station and other subsystems.

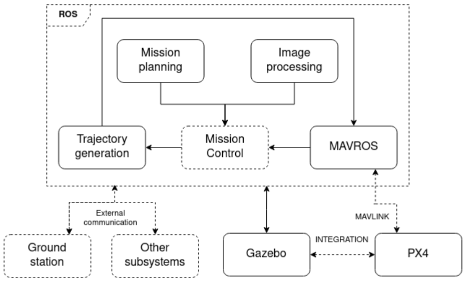

Fig. 9. Software structure for autonomous missions with ROS programming platform

G. Unique Solutions of the VTOL Project

The shell of the VTOL is made of carbon fiber, making the construction stiffer and lighter, than it would be possible with use of glass fiber. The uniqueness of the project is not the construction itself, but its modularity. Due to vast operational applications of the construction, the VTOL is much more flexible than standard builds. Its construction allows mounting various modules for specialized operations, what makes it not only capable of surveillance from the sky but also from the ground, when working as mothership for a ground vehicle, as well as capable of delivering vaccines to hard-to-reach areas. The back part of the hull can be equipped with a high computational SBC (single-board computer) for image processing, but also with extra energy source to extend flight time and distance for remote operations.

IV. AUTONOMOUS MISSIONS

Autonomous missions refer to the tasks that VTOL UAVs perform without human intervention. Described missions include tasks of vaccine distribution, medical delivery and precise agriculture.

A. Targeted plant protection

Autonomous drones for targeted plant protection can revolutionize the fight against plant illnesses and diseases [1]. The solution involves the VTOL aircraft equipped with a camera, spraying module, and computing unit. The cellular network provides server communication with no need for external antennas and reliability of the connection. It operates according to the following idea and scenario, illustrated by Fig. 10. Firstly, the UAV scans given crops in fixed-wing mode and exploits AI (YOLOv5 neural network) and computer vision algorithms to detect diseased plants or weeds.

Then it precisely determines the positions of detected plants and sends data to the server, which later can be visualized on the map with photos and descriptions (with a classification of disease), providing helpful feedback for the system operator. After scanning, the UAV proceeds to the spraying phase and transitions to multi-copter mode. It flies to each localized sick plant, positions itself precisely above the target, applies appropriate plant protection products, and logs the result.

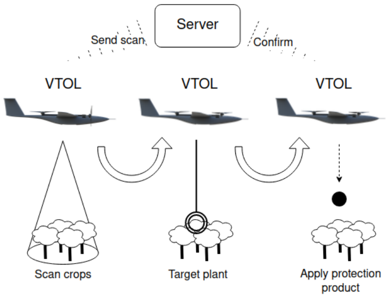

Fig. 10. The course of the targeted plant protection mission with VTOL aircraft

The solution was successfully tested during the nationwide competition Droniada 2021 [17], where it won first place. The task was to perform a targeted plant protection fully autonomous mission, where plants were represented by different geometric figures and protection products by paintball balls (Fig. 11). The accuracy of dropping balls was 1 m when the UAV hovered at 5 m. One of the essential advantages of using autonomous VTOL UAVs for targeted plant protection is the ability to cover large areas quickly and efficiently while reducing the need for manual labor.

Fig. 11. Example of figures detection with YOLOv5 algorithm, during Droniada 2021

B. Distribution of oral vaccines for wildlife

Oral vaccination of wildlife is an important worldwide concern [18], [19]. All over the globe, countries struggle with a need to vaccinate wildlife in order to protect them from spreading dangerous diseases across animals, which can later be transmitted to humans. Usually, the vaccines are provided as an edible packet containing vaccines inside. They are dropped mainly from human-crewed aircraft, which are expensive to maintain. The idea is to use a VTOL UAV to vaccinate smaller areas (Fig. 12) with a planned mission. For that, we created a dedicated deployment module (Fig. 13), which was firstly designed for DJI S900 multicopter and then adjusted to VTOL cargo space. The module is equipped with a GPS receiver and ESP32 microcontroller, allowing control of the vaccine deployment process. Various functionalities were implemented to simplify the use of the module, like the system storing all needed data, including precise localization of the deployment, the ID number of the packet, or information if the packet was correctly deployed. Collected data can then be exported in KML format and visualized on a map using external software, e.g., Google Earth. The developed module received the international prize "Prix Eiffel" of F.F.I. (Federation Francaise Des Inventeurs), and a Gold Medal on the 15th INTARG (International Invention and Innovation Show) 2022 [20]. The use of VTOL UAVs for this mission can significantly reduce costs due to the small size of the UAV and no need for a specialized crew onboard. Furthermore, UAVs are much quieter than a plane and cause less disruption to the wildlife in the area.

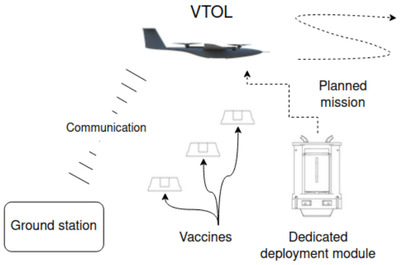

Fig. 12. Mission with spreading vaccines with VTOL aircraft

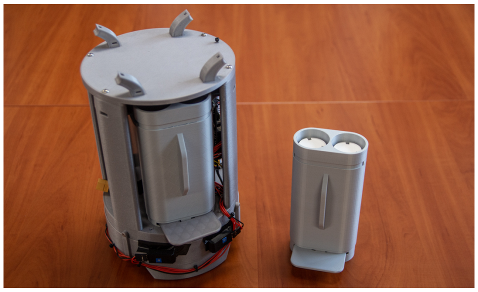

Fig. 13. Dedicated deployment module for vaccinations

C. Emergency medicine delivery

Rapid delivery of medical supplies is critical in emergencies where it can save people's lives. The idea is to use aircraft to drop an RC (remote-controlled) rover in a designated location. VTOL flies to the remote area in fixed-wing mode and changes its mode to multi-copter mode after reaching it. The operator can precisely choose the place of the rover's delivery based on GPS coordinates and a video stream. Then the VTOL UAV autonomously hovers over a desired location and releases the payload. Later, the VTOL UAV is used as a transceiver (Fig. 14), forwarding radio transmission and video stream between the ground station and the deployed rover, allowing for controlling the RC rover in long-range operation and avoiding signal interferences caused by obstacles on the way. The ground station uses a tracker which aligns the directional antenna into the direction of the UAV. The video is transferred using an 5.8GHz video transmitter (VTX). The video stream is then received and displayed on the ground station. To keep the RC rover in the line of sight for extending its control range, the VTOL UAV flies in a circular pattern around the drop location, providing a wide-area overview of the surroundings. A dropped RC rover precisely delivers needed medicine to a given location unavailable for UAV, allowing full communication with a person in helping through a mounted camera and microphone. In the future, a system can also be developed to make the rover fully autonomous. The ground vehicle may be equipped with other sensors, such as a thermal imaging camera or LIDAR (Light Detection and Ranging), which would help to explore the area of interest [21].

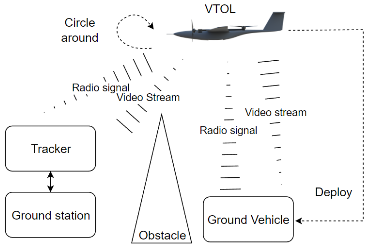

Fig. 14. Mission with VTOL aircraft and car

V. CONCLUSION

In conclusion, VTOL technology has become an increasingly important area of research and development. Due to the unique combination of benefits of both multi-copter and fixed-wing aircraft, it can operate in such areas as agriculture, surveillance, delivery, inspections, emergency services, and military. The High Flyers team from the Silesian University of Technology has developed a VTOL UAV of its proprietary, custom construction for specialized missions. The design of the UAV was discussed by individually describing the mechanical design, mathematical modelling, control system, CFD simulation, and possible afterward expansion.

The paper also discussed the autonomous missions for the designed fixed-wing VTOL UAV and what showcased its capabilities and potential in solving real-world problems. VTOL UAVs have proven their efficiency and ability to help in various situations, such as search and rescue missions, dropping oral vaccines for wildlife, or targeted plant protection. Developed solutions were based on real-life experience and have been recognized in several competitions.

Overall, VTOL technology has great potential to improve efficiency, safety, and accuracy in a wide range of industries and economies. Further development and research can have a significant impact in various areas.

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