MAV Development Towards Navigation in Unknown and Dark Mining Tunnels*

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Abstract—The Mining industry considers the deployment of Micro Aerial Vehicles (MAVs) for autonomous inspection of tunnels and shafts to increase safety and productivity. However, mines are challenging and harsh environments that have a direct effect on the degradation of high-end and expensive utilized components over time. Inspired by this effect, this article presents a low cost and modular platform for designing a fully autonomous navigating MAVs without requiring any prior information from the surrounding environment. The design of the proposed aerial vehicle can be considered as a consumable platform that can be instantly replaced in case of damage or defect, thus comes into agreement with the vision of mining companies for utilizing stable aerial robots with reasonable cost. In the proposed design, the operator has access to all on-board data, thus increasing the overall customization of the design and the execution of the mine inspection mission. The MAVs platform has a software core based on Robot Operating System (ROS) operating on an Aaeon UP-Board, while it is equipped with a sensor suite to accomplish the autonomous navigation equally reliable when compared to high-end and expensive platforms.

I. INTRODUCTION

Recently, deployments of Micro Aerial Vehicles (MAVs) are gaining increasing attention, especially in the mining industry [1]. The autonomous navigation of the MAV, equipped with a sensor suite has the ability to collect information, such as images, gas level, dust level, monitor the personnel, explore unknown and production areas, and minimize service times. At the same time, the deployments of MAVs increase the production and the overall safety in the mining industry, while reducing the overall operation costs aligned with the envisioned mine of Zero Entry Production Areas (ZEPA) [2].

Furthermore, the harsh mining environments are characterized from a lack of illumination, narrow passages, wind gusts, dust and in general conditions that have a direct affect the performance of the platforms and in the worse case may cause failure in system components or even result to collision and crashes. Moreover, the commercially available MAVs rely on Global Positioning System (GPS) or visual sensors, or both for performing a position estimation, however underground mines are GPS-denied environments and due to lack of any natural illumination and prominent visual and geometric features, the vision-based positioning methods are not reliable. Additionally, commercially available platforms provide manual or semi-autonomous flights, which require a pilot with a direct line of sight to the platform, a case which cannot be guaranteed in dark tunnels with multiple turns and crosses.

The main objective of this article is to propose a low cost and modular MAV platform, as depicted in Figure 1, for autonomous navigation in dark tunnels. The platform is equipped with a 2D lidar, a single beam laser range finder, LED light bars, a PX4 optical flow, a forward looking camera, a flight controller and an on-board computer, while the software architecture is developed based on the equipped sensor suites to establish fully autonomous navigation. The proposed configuration of the MAV has been specifically designed for a direct deployed in underground mines, without a natural illumination and by that demonstrating the capability for fully autonomous MAVs navigation in such environments.

Finally, this article discusses all the needed components in order to enable further hardware developments towards the autonomous navigation in dark tunnels. Although this work showcases the platform in tunnel navigation, the system can be deployed in similar missions including subterranean exploration [3], or Mars canyon exploration [4].

Fig. 1: The proposed low-cost MAVs platform with attached body fixed frame B.

The rest of the article is structured as it follows. Initially, the state of the art of MAV development is presented in Section II, followed by the platform architecture in Section III, which discusses the corresponding hardware and software components. In Section IV the performance of the proposed platform is evaluated in an underground mine tunnel and finally in Section V a summary of the findings is provided.

II. RELATED WORKS

Nowadays, industry and academic sectors develop MAVs for different applications. The majority of the developed plat-
forms by commercial companies do not provide access to raw sensor measurements or tuning parameters of the controllers. Additionally, these platforms do not allow for hardware modifications and their performance is limited to semi-autonomous navigation especially in indoor environments. These factors limit their usage and functionality in challenging environments, such as underground mine tunnels, where the platform should be modified based on the application requirements. As an example, the commercially available quad-copter Parrot Bebop 2 [5] is equipped with a forward looking camera, an optical flow sensor and a sonar sensor facing down, it weights 0.5 kg and it able to provide 25 mins of flight time. The platform is Robot Operating System (ROS) compatible and can be used for research or teaching purposes. However, it does not have an onboard computer and provides a WiFi link so that all the computations should be on a ground station. Moreover, the user cannot modify or add extra sensors to the system, while there is no access to the low-level control architecture and sensor measurements. Another commercial product is the DJI Matrice 100 [6], which is a fully customizable and programmable flight platform that can be equipped with sensors required for performing an autonomous underground navigation, however it does not allow access to the low-level controllers and the raw sensor data, thus increasing the overall complexity for the fusion of new sensor measurements. Moreover, the basic price of the platform without the sensor suites and computing unit starts from 3300 USD. Table I compares commercial MAVs with the proposed platform, emphasizing on important factors such as cost, ROS compatibility, sensor measurement accessibility, etc.

TABLE I: The comparison of the existing MAVs with proposed platform.

| Platform                  | Cost | Sensors for all payload | Computer unit | ROS | Data accessibility | Low-Level Control | Data fusion | Spare part availability |
|--------------------------|------|-------------------------|---------------|-----|--------------------|-------------------|-------------|------------------------|
| Intel Airo      Low     ✓ ✓ ✓ ✓ ✓ ✓ Low    |      |                        |               |     |                   |                  |             |                        |
| DJI Matrice 100         High  X X X Moderate ✓ ✓ High            |      |                        |               |     |                   |                  |             |                        |
| Yuneec H520             High  X Moderate X Moderate ✓ ✓ Moderate |      |                        |               |     |                   |                  |             |                        |
| AscTec Neo              Very high X ✓ ✓ ✓ ✓ Moderate |      |                        |               |     |                   |                  |             |                        |

There are multiple open-source platforms developed for teaching proposes, such as the CrazyFlie [7], the Parrot Minidrone [8] and the PiDrone [9]. The CrazyFlie is a small quad-copter, which provides 4 min of flight time, without pay-load and due to its size, it cannot compensate wind-gusts. The parrot Minidrone has the same drawbacks as the CrazyFlie, while the platform is not ROS compatible, a factor that is drastically limiting its usage. The PiDrone is a ROS compatible quad-copter with an onboard Raspberry Pi that runs Python and provides a 7 min flight time. Additionally, the PiDrone provides an accessible and inexpensive platform for introducing students to robotics. The drawback of this platform is lack of proper sensor suites for dark tunnels and the corresponding limited computational power for advanced

algorithms and methods such as Visual Inertia Odometry (VIO).

Furthermore, within the related literature of MAVs in underground mining operations, few research efforts have been reported trying to address challenging tasks within the mine. In [10] a visual-inertial navigation framework has been proposed, while the system was experimentally evaluated in a real-scale tunnel environment, simulating a coal mine, where the illumination challenge was assumed solved, while the platform is based on Ascending Technologies Pelican quad-copter and the authors have performed a low-level adaptation of a commercial platform, which is a complex task. In [11], a more realistic approach, compared to [10], regarding the underground localization has been performed. The FireFly hexacopter from Ascending Technologies, equipped with a Visual Inertia (VI) and a Hokuyo URG-04LX 2D laser scanner was used and it was manually guided across a vertical mine shaft to collect data for post-processing. In [12], the authors addressed the problem of estimation, control, navigation and mapping for autonomous inspection of tunnels using a DJI F550 platform equipped with a Velodyne PuckLITE lidar, four Chameleon3 cameras, a PixHawk optical flow and an Intel core i7 NUC PC. The overall approach was validated through field trials, however in this case a high-end and expensive sensor suit was utilized while flying.

III. PLATFORM ARCHITECTURE

In this article, the proposed quad-copter is designed to be inexpensive, modular, autonomous, while it provides access to all the onboard raw sensor measurements. In the sequel, the hardware and software components of the overall architectures are discussed.

A. Hardware Components

The Enzo330 V2 330mm Wheelbase frame is selected, due to a dense market availability, low cost, durability and customizability. Figure 2 presents the corresponding frame structure. However, few modifications are performed to improve the frame functionality and durability as depicted in Figure 3. The top part of the frame has been redesigned to allow installation of the computing unit, power modules and
additional sensors. For durability reasons, the top part has been made out of carbon fiber. Additionally, extra damping for the flight controller was introduced to reduce the vast amount of vibrations generated by the motors.

![Image](image_url)

Fig. 3: Modified top part of the frame with components installed

The landing gear has been designed and 3D printed to provide sufficient space for the sensors located on the bottom, such as an optical flow sensor and a front facing camera. Figure 4 depicts the modified proposed frame, equipped with sensor suits, while highlighting the dimensions of the platform. Moreover, the Multistar Elite 2308-1400 motors, carbon fiber T-Style 8x2.7 propellers and the Turnigy Multistar BLheli 32 ARM 4 in 1 32bit 31A Electronic Speed Controllers (ESCs) have been selected based on the frame dimensions, estimated weight of the complete platform and the power required by the motors.

Furthermore, to establish the autonomous flight, the proposed quad-copter is equipped with the hardware modules depicted in Figure 5, while Table II provides the cost of each component and the total cost of the platform. In the following Table II the core hardware components are discussed.

| Subsystem                  | Item                                | Cost  |
|----------------------------|-------------------------------------|-------|
| Computation                | Aaeon UP-Board                      | $190.00 |
| Avionics                   | NAZE 32 REV 6 FCU                   | $35.00 |
| Avionics                   | 4x Multistar Elite 2308-1400 Motors | $85.00 |
| Avionics                   | Turnigy Multistar 4-in-1 ESC        | $45.00 |
| Avionics                   | 4x 8x2.7 carbon fiber propellers    | $10.00 |
| Avionics                   | Enzo330 Frame with upgraded top plate | $30.00 |
| Sensors                    | RPLidar A2M8                        | $280.00 |
| Sensors                    | LIDAR-Lite 3                        | $130.00 |
| Sensors                    | PX4FLOW                             | $135.00 |
| Sensors                    | PS3 Eye Camera                      | $30.00 |
| Power                      | Battery and DC-DC converter         | $50.00 |
| Light                      | LED bars and current drivers        | $75.00 |

**TABLE II: List of the components**

Finally, for collecting visual data, the PlayStation 3 Eye camera has been used that has the ability to capture a video stream with a resolution of $640 \times 480$ pixels with 60 fps or $320 \times 240$ pixels with 120 fps. The camera has 56-75 degrees of horizontal field of view and the image stream can be used as Augmented Reality (AR) for human operator or vision based algorithms.

3) Additional light sources: Several extra light sources have been installed on the aerial platform to provide illumination for the visual sensors. Two 10 W LED bars have been installed on the front part of the quad-copters’ arms and the constant current is provided by dedicated power LED drivers Recom RCD-24-0.70/W/X3. The drivers allow to modify the constant current, which will indicate a change in the light luminosity by Pulse Width Modulations (PWMs) and analogue input signals. The measured light illumination on...
the 1 m distance from the MAVs with the maximum power utilized was 2200 lux. Furthermore, the power LED bars and the drivers are placed under the propellers to utilize the airflow during the flight as a forced cooling. Additionally, 4 low power 10 mm LEDs have been installed on the bottom side of the MAVs for creating an optical flow sensor.

4) Battery: After multiple tests, the optimal battery has been selected given parameters such as size, weight, voltage and energy stored. Proposed battery, ZIPPY Compact 3300mAh 14.8V 40C 4S1P with weight of 360g provide flight time of 12 min in no wind conditions.

B. Software Architecture

The general scheme of the proposed software architecture is presented in Figure 6. The software architecture of the developed platform consists of the navigation, control, state estimation and visual feedback components.

The navigation component, based on the authors previous works [1], [14] and [15], incorporates data from the on-board front facing camera or the 2D lidar for following the tunnel axis. The output of the navigation component includes the heading rate command for the MAV to correct the MAV heading towards the tunnel axis and the velocity and altitude references for controller components to hover at a fixed altitude and to avoid collision in case the platform flies close to obstacles. Furthermore, a state estimation module provides estimated values for altitude $z$, velocities along $x$, $y$, $z$ axes and attitude (roll and pitch) of the platform from the IMU, the optical flow sensor and the downward looking laser range finder measurements. It should be highlighted that an accurate estimation of the heading angle is not possible as magnetometer is not reliable, especially in an underground mine and Global Navigation Satellite System (GNSS) is not available for underground areas. Moreover, the navigation commands, as well as the state estimation outcome, are sent to the Nonlinear Model Predictive Control (NMPC) controller [16] component, which generates control commands (thrust, roll, pitch, yaw-rate) for the flight controller. Finally, the visual feedback component consists of the sequential stream of the on-board camera images, which can be used for AR.
IV. PLATFORM PERFORMANCE

This section describes the platform performance and results from each component, while the platform performs autonomous navigation in a real scale underground mine in Sweden [17], [18]. Link: https://youtu.be/dxMUx49a_uo provides a video summary of the obtained results. The location of the field trials was 790 m deep, without any natural illumination sources and with a tunnel width of 6 m and a height of 4 m. The area does not have strong corrupting magnetic fields, which could affect the platform sensors, while Figure 7 depicts one part of the visited underground mine.

![Photo of a visited underground mine in Sweden.](image)

During the performed experiment, the desired altitude was selected as 1 m with a constant velocity of 0.1 m/s aligned with the x-axis, while the platform is equipped with a PlayStation 3 Eye Camera and the LED light bars that provide a 460 lux illumination in 1 m distance. Moreover, a potential field method based on a 2D lidar was utilized for avoiding collisions to the tunneling walls, while measurements from a 2D lidar or a camera was used to correct the heading of the platform towards the open spaces or the tunnel axes respectively.

![Obtained 2D map from laser scans while flying.](image)

The downward looking single beam laser range finder can be directly used for altitude regulation and Figure 8 depicts the controlled achieved altitude over time for the proposed quad-copter during field trials in an underground tunnel. In this experimental case, there were no accurate height references available in the mine to evaluate the range finder measurements. However, from the overall performance of the platform, a constant altitude during the mission was successfully achieved.

![Obtained 2D map from laser scans while flying.](image)

The velocity estimation for the developed system is provided from the optical flow system, however due to lack of features and illumination it is corrupted from noise measurements, thus the raw measurements were passed through low-

![Altitude measurements from the downward facing range finder over time during a test flight in an underground tunnel.](image)

The 2D laser scanner was used by algorithms for obstacle avoidance and heading correction. The collected range measurements, during the flight, can be post processed to provide a 2D map of the area. The laser scans are processed from a Lidar SLAM method [19] that is available in the ROS framework, to generate a 2D occupancy map. The map characterizes the occupied and free space of the visited underground tunnel, while it is generated online with a 1 Hz update rate and a resolution of 0.05 m/pixel, while the robot covered an approximate distance of (x,y)=(70 m,85 m)

![Obtained 2D map from laser scans while flying.](image)

\(^1\text{https://youtu.be/dxMUx49a_uo}\)
pass filter. Figure 10 demonstrates the velocity state estimate during the field trials in the underground tunnel.

![Fig. 10: Time evolution of the $v_x$ and $v_y$ raw (red) and filtered (blue) corresponding velocities measurements from the downward facing optical flow sensor during a test flight in an underground tunnel.](image)

The online information from the on-board sensors like the current altitude, MAV status, the 2D top down lidar map and the collision prediction can be overlaid to the image stream and displays to the operator as depicted in the attached video.

V. CONCLUSIONS

In this work, a low-cost high-performance quad-copter has been proposed. The developed solution is ready to fly in underground tunnels while accomplishing inspection tasks. The operator of the platform has access to all sensor measurements, as well as the information for the MAV status, assisting the algorithm development, the software implementation and the overall operation both in the preparation of the mission as well as during the mission. Finally, the developed MAV has been deployed in an unknown dark underground tunnel and successfully performs fully autonomous navigation.

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