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A METHODOLOGY FOR EVALUATING AND COMPARING UNMANNED INSPECTION PLATFORMS IN UNDERGROUND AND INDOOR ENVIRONMENTS

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by
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Abstract

This report summarizes a research project focused on development of a methodology for evaluating the performance of various unmanned aerial vehicles (UAVs, commonly referred to as drones) and robotic platforms in GPS-denied environments, highlighting a clear stratification based on technological sophistication and design intent. A series of flight trials were designed and implemented in various environments including indoor spaces with various geometries and obstacles, and an underground mine. These trials examined signal range from the unmanned platform to the controller, the ability to navigate through confined spaces and obstacles, the overall ease-of-use and responsiveness of controls, as well as specialized features and abilities of each platform.

Highly advanced drones like the Elios 2 and Elios 3 exhibit superior maneuverability and reliability due to their advanced sensor suites and navigation algorithms, though their high cost limits their use to specialized applications. SPOT, a four-legged robot, offers intuitive control and unique features like an extendable arm, but its limited signal range and large size confine its use to line-of-sight operations. Conversely, custom-built drones with minimal sensor packages, such as the Tommyknocker, perform well in confined spaces, providing a cost-effective option for high-risk areas despite their lower camera resolution and shorter battery life. Mid-level drones like the Phantom 4 and Mavic 3E, not specifically designed for indoor or GPS-denied applications, show suboptimal performance in these environments due to their sophisticated obstacle avoidance sensors. However, the Mavic 3E can show superior performance in larger underground spaces and exhibit long battery life and signal range.

The study underscores the necessity of aligning drone capabilities with operational requirements. It was demonstrated that both highly specialized and simple platforms can be effective in the appropriate contexts, whereas general-purpose drones may struggle but can be used effectively in some situations.

Keywords: UAV, drone, flight trial, performance evaluation, underground mine, GPS-denied environment

Dedication

To my mom and dad, for all their support and love. To my sister, for her constant inspiration and belief in me.

Acknowledgements

I would like to express my deepest gratitude to my advisor, Mary MacLaughlin, for her guidance and mentorship throughout this project. Mary’s insightful feedback and encouragement have been invaluable in shaping this research and my academic journey. I am also immensely thankful to all those who assisted in the drone flight trials and data collection for this study. Your expertise and dedication ensured the successful execution of the experimental phase of this research. Special thanks to Karl Farber, Chris Langhoff, Jim Jonas, Rusty Turner, and Kodis Campbell for their expert piloting and operational skills, and thanks to Abhishek Choudhury for lending me the use of his robot platform for this study. Additionally, I extend my appreciation to my family and friends for their patience, encouragement, and belief in me during this endeavor. Finally, I acknowledge the support of Montana Technological University for providing the resources and facilities essential for this research. Thank you all for being part of this journey and contributing to the successful completion of this research project.

Table of Contents

List of Tables

List of Figures

1. Introduction

Unmanned aerial vehicles (UAVs), or drones, have revolutionized various industries, including agriculture, construction, and surveillance. However, the vast majority of UAV operations are accomplished with Global Positing System (GPS) based navigation tools. The utilization of UAVs in GPS-denied environments such as mines, tunnels, and indoor spaces, presents unique challenges and opportunities. In these confined and often hazardous spaces, drones must navigate complex terrain, withstand adverse conditions, and maintain communication with operators. As such, there is a growing need to develop a comprehensive methodology to evaluate and compare the performance of different UAV platforms in underground and indoor environments.

This research aims to address this need by proposing a systematic approach to assess the capabilities of various drone models within underground settings. The UAVs selected for this study include the DJI Phantom 4 and Mavic 3 Enterprise, the Flyability Elios 2 and Elios 3, and the iFlight BumbleBee V2 (Tommyknocker). This study also includes a walking robot SPOT from Boston Dynamics. These platforms represent a diverse range of features and capabilities, making them suitable candidates for comparison.

The parameters tested encompass critical aspects of UAV performance in confined space environments, including flight time/battery life, range (maximum distance from operator), obstacle avoidance features, capabilities of onboard sensors, ability to take off and land indoors, and durability against dust/debris and water. Each parameter was evaluated under controlled conditions to ensure consistent and reliable results.

Flight time and battery life are crucial factors, as longer endurance allows drones to cover more ground and complete missions efficiently. The range of a drone determines its operational scope within underground structures, influencing its suitability for various applications. Additionally, obstacle avoidance features are essential for navigating through confined spaces without collision, safeguarding both the drone and the environment.

The capabilities of onboard sensors, such as cameras and LiDAR, play a vital role in data acquisition and mapping underground terrain. Furthermore, the ability of a UAV to take off inside a mine tunnel or indoor area is indicative of its adaptability to confined spaces and operational flexibility. Lastly, the durability of UAVs against dust/debris and water is imperative for ensuring reliable performance in harsh underground conditions.

By systematically evaluating these parameters across different drone platforms, this research provides valuable insights into their strengths, weaknesses, and suitability for diverse underground applications. The findings of this study contribute to informed decision-making processes for selecting the most appropriate UAV platform based on specific operational requirements.

The development of a methodology to compare drone platforms for underground environments is essential for advancing the use of UAV technology in industries such as mining, infrastructure inspection, and search and rescue operations. This research endeavors to address this gap by offering a systematic framework for evaluating and benchmarking UAV performance in challenging underground settings.

2. Background

The motivation for this research stems from the growing need to explore and optimize drone technologies for indoor and underground operations across industries such as mining, construction, infrastructure inspection, and public safety. Understanding how different drone platforms perform under varying conditions will inform the development of tailored solutions to maximize efficiency and safety in challenging environments.

In recent years, significant research efforts have been directed towards evaluating the performance of UAVs in specialized operational contexts, including challenging environments such as underground spaces and GPS-denied areas. One notable study conducted by researchers from North Carolina A&T State University in collaboration with the North Carolina Department of Transportation focused on assessing the suitability of commercially available UAV platforms for bridge inspection missions (Karimoddini et al., 2022). Through a series of experiments and test flights conducted selected structures, the team explored various criteria including flight performance, situational awareness payload and sensor capabilities, and communication quality. To avoid endorsing a specific platform, the study referred to the UAVs only as UAV1 through UAV4. Although the focus of this research does not include GPS-denied environments such as indoor or underground settings, the methodology of evaluating UAV platforms through a series of flight trials can be adapted to other environments.

Similarly, the Defense Advanced Research Projects Agency (DARPA) initiated the Subterranean (SubT) Challenge to spur innovation in underground operations, attracting research teams worldwide to address autonomy, perception, networking, and mobility challenges in subterranean environments (DARPA, 2021). These areas of interest covered critical criteria for successful robotic operations such as the ability to map and navigate in complex and dynamic environments where there could be harsh conditions such as confined spaces and steep inclines/declines, smoke, mist, debris, and low light, while maintaining communication with operators from limited line of sight. The competition was divided into virtual and systems components, where the virtual teams worked to develop algorithms, and the systems teams focused on developing physical solutions in realistic field environments. Different scenarios were presented for the experiment including simulated search & rescue in collapsed mines and caves. The objective for each team was to use a robotic system to search, detect, and provide spatially referenced locations of various objects. This challenge provides an insightful way to conduct simulated real-world scenarios for robotic platforms, and a way to quantify each team's success. This challenge can be adapted and further explored with other experiments, and can be used to quantity the overall performance of different platforms.

Additional research has come from the University College Cork in Ireland, which outlined UAV navigation techniques in confined underground spaces, addressing challenges such as lack of GNSS signals, poor lighting conditions, and obstacle avoidance systems (Zhang et al., 2023). While this research proposes strategic solutions for addressing these challenges, it does not delve into comparing how different UAV platforms perform against each other.

Furthermore, graduate student Rachel Becker's thesis research at Montana Technological University focused on developing a methodology for evaluating UAV-based photogrammetry in underground mines, assessing collision avoidance capabilities and the data quality and accuracy provided by four different drone platforms. This research provides a procedure for developing simulated flight trials and evaluating UAV performance based on qualitative observations of each flight (Becker, 2019).

These previous studies have highlighted the significance of selecting appropriate UAV platforms based on specific operational requirements and environmental constraints. However, comprehensive research directly comparing the performance of diverse drone platforms in GPS-denied indoor and underground settings remains limited. This research aims to bridge this gap by establishing a systematic methodology for evaluating and comparing UAV performance across controlled indoor and underground environments.

3. Research Objectives and Approach

By conducting rigorous flight trials and analyzing key performance metrics, this research contributes valuable insights into the strengths and limitations of various unmanned inspection platforms for use in GPS-denied indoor and underground environments, ultimately informing decision-making processes for selecting the most suitable drones for specific applications. The outcomes of this study have the potential to advance UAV technology and enhance operational capabilities in challenging and dynamic environments where traditional data collection methods may be impractical or inefficient.

This project was designed to produce several outcomes, including the identification of strengths and weaknesses among the selected UAV platforms in indoor and underground environments, the establishment of guidelines for selecting the most suitable UAV platform based on specific operational requirements and environmental constraints, and development of recommendations for enhancing UAV design and technology to optimize performance in challenging operational contexts.

The primary objective of this research was to establish a systematic methodology for evaluating and comparing diverse UAV platforms available for operations in indoor and underground environments. One important aspect of this study was to assess the performance of selected drone platforms across challenging settings, including an indoor three-story building, a long indoor tunnel, and various passageways within an underground mine.

To achieve this objective, the research commenced with the careful selection of six diverse drone/robot platforms that cover a range of unique features and capabilities. This set encompasses both low-end and high-end remotely piloted vehicles to evaluate a spectrum of performance levels. One of the chosen drones is a basic, entry-level model known for its affordability and simplicity, representing a common option for introductory drone users. Additionally, we included two mid-range commercial UAVs renowned for stability and imaging capabilities, ideal for standard outdoor aerial surveys. To explore advanced features, two high-end professional UAV platforms were selected that were explicitly designed for underground and indoor inspections with sophisticated obstacle avoidance and sensors . We also used a custom-built drone designed specifically for GPS-denied environments, constructed from a self-build kit, which provides insights into specialized applications requiring navigation without reliance on satellite positioning. Lastly, we also incorporate a four-legged walking robot to compare its performance with aerial vehicles. This diverse selection captures a comprehensive range of drone functionalities and performance levels, enabling thorough comparisons across various operational scenarios.

A set of trials was designed and conducted in controlled environments to evaluate the performance of these drone platforms. Specific scenarios include flight trials within an indoor three-story building to assess maneuverability, obstacle avoidance, and stability in confined spaces and varying heights. Additionally, exploration of a long indoor tunnel tested drone navigation, communication, and stability under low-light conditions and GPS-denied environments. Flight tests in different passageways within an underground mine were conducted to evaluate endurance, communication reliability, and adaptability to dynamic operational conditions.

During the performance trials, key performance metrics were monitored, including maneuverability, stability, collision avoidance effectiveness, endurance, and communication reliability. The data collected, both quantitative and qualitative, enable a comprehensive analysis and comparison of the drone platforms across different environments based on predefined metrics. The methodology development process involved standardizing flight trial protocols to ensure consistency and comparability, defining specific tasks and scenarios to simulate real-world operational challenges, and incorporating safety protocols to mitigate risks associated with indoor and underground operations.

4. Platform Technical Specifications

The technical specifications of each platform are provided by the drone manufacturers. The Tommyknocker is a custom-built drone kit developed by iFlight, using the BumbleBee V2 frame. The Tommyknocker includes custom modifications and Cree LED lights. The Mavic 3 Enterprise was developed by DJI and is a commercial drone designed for mapping, surveying, and inspection along with hobby applications. The Phantom 4 was also developed by DJI and has been discontinued as of 2023; however, there are many Phantom 4 drones still on the market and in use across the globe. It is commonly used for filmography as well as mapping and surveying. The Elios 2 and Elios 3 were developed by Flyability and are specifically designed for indoor inspection purposes. SPOT is an agile four-legged walking robot developed by Boston Dynamics.

Table I provides a summary of the various platforms incorporated in this study, including information on the manufacturers, release years, and the estimated cost based on available information. For the Tommyknocker and Phantom 4 the cost is an estimation. The Tommyknocker is a custom-build kit that can be enhanced with outside features and does not include the cost of propellers or a battery. The Phantom 4 is no longer sold by DJI and is available from second-hand retailers for a variety of prices depending on the condition. The cost of all the drones can vary depending on additional sensors or packages that are purchased. Images of the unmanned platforms used in this study are pictured in Figures 1-6. The images show the standard platforms provided by the manufacturers.

Table I: Platforms

Platform	Manufacturer	Release Year	Cost	Source
Tommyknocker	iFlight	2020	$400-$600	https://www.getfpv.com/iflight-bumblebee-hd-v2-cinewhoop-3-fpv-racing-drone-w-dji-digital-hd-fpv-system-pnp.html
Phantom 4	DJI	2016	$2,000	https://www.dji.com/phantom-4-pro-v2/specs
Mavic 3E	DJI	2022	$3,600	https://enterprise.dji.com/mavic-3-enterprise/specs
Elios 2	Flyability	2019	$35,000	https://f.hubspotusercontent10.net/hubfs/2602167/ELIOS%202%20Technical%20Specifications%20v1.2.pdf
SPOT	Boston Dynamics	2015	$74,000-$277,000	https://bostondynamics.com/products/spot/

Figure 1: Tommyknocker (https://www.getfpv.com/iflight-bumblebee-hd-v2-cinewhoop-3-fpv-racing-drone-w-dji-digital-hd-fpv-system-pnp.html)

Figure 2: Phantom 4 (https://www.dji.com/phantom-4-pro-v2)

Figure 3: Mavic 3 Enterprise (https://enterprise.dji.com/mavic-3-enterprise)

Figure 4: Elios 2 (https://www.flyability.com/elios-2)

Figure 5: Elios 3 (https://www.flyability.com/elios-3)

Figure 6: SPOT (https://bostondynamics.com/products/spot/)

Table II summarizes the physical attributes of the platforms provided by the manufacturers. The mass of the Tommyknocker was collected using a standard precision gram scale. The mass of each platform includes the battery and standard sensor packages. The Elios 3 weight also includes the LiDAR unit. The sound level was recorded with a Sound Level Machine (SLM) manufactured by Quest Technologies. This provides the sound level of each drone in decibels (Db). Each recording was taken during takeoff from a distance of approximately 5 ft. Noise above 70 dB over a prolonged period of time may cause damage to hearing. Loud noise above 120 dB can cause immediate harm to ears (World Health Organization, 2019).

Table II: Physical Attributes

Platform	Mass (grams)	Dimensions (mm)	Sound Level (Db)
Tommyknocker	590	111 x 93 x 27	81.8
Phantom 4	1380	289 x 289 x 196	87.5
Mavic 3E	915	348 x 283 x 108	76.1
Elios 2	1450	400 x 400 x 400	98.8
Elios 3	2350	480 x 380 x380	88.0
SPOT	31706	1100 x 500 x 610	61.9

Table III summarizes the battery attributes for each platform including specifications on the battery used. Information on battery life, recharge time, and temperature range is extracted from the drone specifications provided by each manufacturer. The Tommyknocker allows multiple battery options and is customizable and shows the battery option used for the study. The remaining drones all require manufacturer specific batteries. Battery life is dependent on factors such as temperature (cold or hot extremes can shorten battery life), age of the battery, additional payloads, and other adverse conditions such as wind. Therefore, the manufacturer provided battery life is likely an overestimation of practical battery life.

Table III: Battery Attributes

Platform	Battery	Battery Life (min)	Full Recharge (min)	Temperature Range °F
Tommyknocker	LiPO 1300mAh	5	60	20 – 95
Phantom 4	DJI Phantom 4 Intelligent Flight Battery 5870 mAh LiPo	30	50	32 – 104
Mavic 3E	DJI Mavic 3 Series Intelligent Flight Battery 5000 mAh LiPo	46	96	14 – 104
Elios 2	Flyability Smart Battery 5200 mAh LiPo	10	60	32 – 122
Elios 3	Flyability Smart Battery 4350 mAh LiPo	9	60	32 – 122
SPOT	Spot Enterprise & Explorer Battery Li-ion	90	60	-4 – 113

Table IV provides the Ingress Protection Code for each drone that has a rating. The Ingress Protection code is an international standard (IEC 60529) that provides a rating to signify the degree of protection a mechanical component has against intrusions of water, dust, or objects. It is a two-digit code, where the first digit represents protection against solid objects, and the second digit indicates protection against liquids. The higher these numbers, the better the protection. The solid rating chart is typically ranked from 0-6, with 0 being no protection and 6 being no ingress of dust. The liquid rating chart is typically ranked from 0-9, with 0 being no protection and 9 being protection from powerful, high pressure water jets. Based on the provided IP codes, the Elios 2 and Elios 3 are protected from solid objects greater than 1mm. The Elios 2 is protected against water droplets, whereas the Elios 3 is protected against water spray from all directions. The Elios 3 LIDAR unit would be protected from dust (no ingress of dust) and resists long periods of immersion under water. SPOT is protected against dust (limited ingress of dust) and is protected against water spray from all directions.

Table IV: Ingress Protection Code

Platform	Environmental Seal	Water Resistance
Tommyknocker	N/A	N/A
Phantom 4	N/A	N/A
Mavic 3E	N/A	N/A
Elios 2	4	2
Elios 3	4	4
Elios 3 LiDAR	6	8
SPOT	5	4

Table V summarizes drone mobility such as the maximum speed in meters per second and the maximum pitch in degrees. This information is extracted from drone specifications provided by the manufacturer. In the context of drone flight, “roll”, “pitch”, and “yaw” refer to the three primary axes of rotation. Roll is rotation around the longitudinal axis (left-right motion), yaw is rotation around the vertical axis (left-right rotation), and pitch is movement along the lateral axis which controls the up-down motion. For a non-aerial drone like SPOT, pitch is defined as the steepness the robot can ascend or climb. The aerial drones can be operated in different modes: Sport, Normal, and Attitude. Sport Mode is optimized for agility and speed with disabled obstacle sensing; however it may still utilize GNSS. Attitude mode is flying without intelligent flight features like GPS positioning and obstacle sensors. Normal mode operates using all available onboard sensors and positioning tools. The maximums provided are the maximum overall speed and pitch in sport mode. Using normal mode or attitude mode may reduce the maximum speed and pitch of the drone.

Table V: Drone Mobility

Platform	Max Speed (m/s)	Max Pitch (degrees)
Tommyknocker	≈36	N/A°
Phantom 4	20	42°
Mavic 3E	19	35°
Elios 2	6.5	17°
Elios 3	7	17°
SPOT	1.6	45°

Table VI summarizes the lighting systems for each platform. The Tommyknocker, Phantom 4, and Mavic 3E all used custom external light systems. The Elios 2, Elios 3, and SPOT all have onboard light systems built into the platform, and information on light output is provided by the manufacturers. The light output in lumens is a measurement of the total amount of visible light a light source emits. The higher the lumen, the brighter the light will appear. The Elios platforms have significantly more light output than any of the other platforms. SPOT has the lowest light output; however, the arm of the robot has the ability to hold additional light sources such as a flashlight if needed. The Tommyknocker uses the Cree XM-L2 LED lights, with light output provided by the Cree manufacturer. For this study, FoxFury Rugo lights were attached to the Phantom 4, and FoxFury D3060 lights were attached to the Mavic 3E. Light output and light battery life is also provided by the manufacturer.

Table VI: Drone Light Systems

Platform	Light System	Light Output (Lumens)	Light Battery Life (min)
Tommyknocker	Cree XM-L2 LED	1198	N/A
Phantom 4	FoxFury Rugo	620	90
Mavic 3E	FoxFury D3060	200	90
Elios 2	On-board system	10000	N/A
Elios 3	On-board system	16000	N/A
SPOT	On-board system	105	N/A

Table VII summarizes onboard collision avoidance systems and other additional protective features of each platform. This information is extracted from the technical specifications provided by each manufacturer. The protective carbon-fiber cage for the Elios drones provides 360° protection from collision with objects. The Tommyknocker has propeller guards, which helps to protect the propellers from breaking even if the drone crashes. The Phantom 4 has long legs for landing which helps to prevent debris from being kicked up into the propellers. SPOT has a durable frame and arm. The Mavic 3E has a collapsible design which helps to protect the drone during transport.

Table VII: Drone Collision Avoidance Systems & Protective Features

Platform	Collision Detection System	Protective Features
Tommyknocker	N/A	Propeller Guards
Phantom 4	GPS / GLONASS	Landing Legs
Mavic 3E	Vision System 360°	Collapsible design
Elios 2	On-board stability sensors	Protective carbon-fiber cage
Elios 3	SLAM-based stabilization	Protective carbon-fiber cage
SPOT	Moving Object Detection	Durable frame

Table VIII summarizes the drone sensors and cameras each platform is equipped with along with video and photo resolution if applicable. This information is extracted from the technical specifications provided by each manufacturer. The Tommyknocker, Phantom 4, Mavic 3E, and SPOT are all equipped with a single main camera. The Elios 2 additionally has a thermal camera, and the Elios 3 has a thermal camera as well as a LiDAR sensor. Resolution is recorded pixels/megapixels with frames per second (fps) indicating how many images can be taken in a single second. More pixels provides a higher resolution. Higher resolution images may slow down the possible number of frames per second. 4K resolution is 4 times higher resolution than 1080p, which leads to a significantly sharper and more detailed image. The Phantom 4, Mavic 3E, Elios 2, and Elios 3 can all record in 4K. The Tommyknocker has the lowest resolution of all the platforms.

Table VIII: Drone Sensors

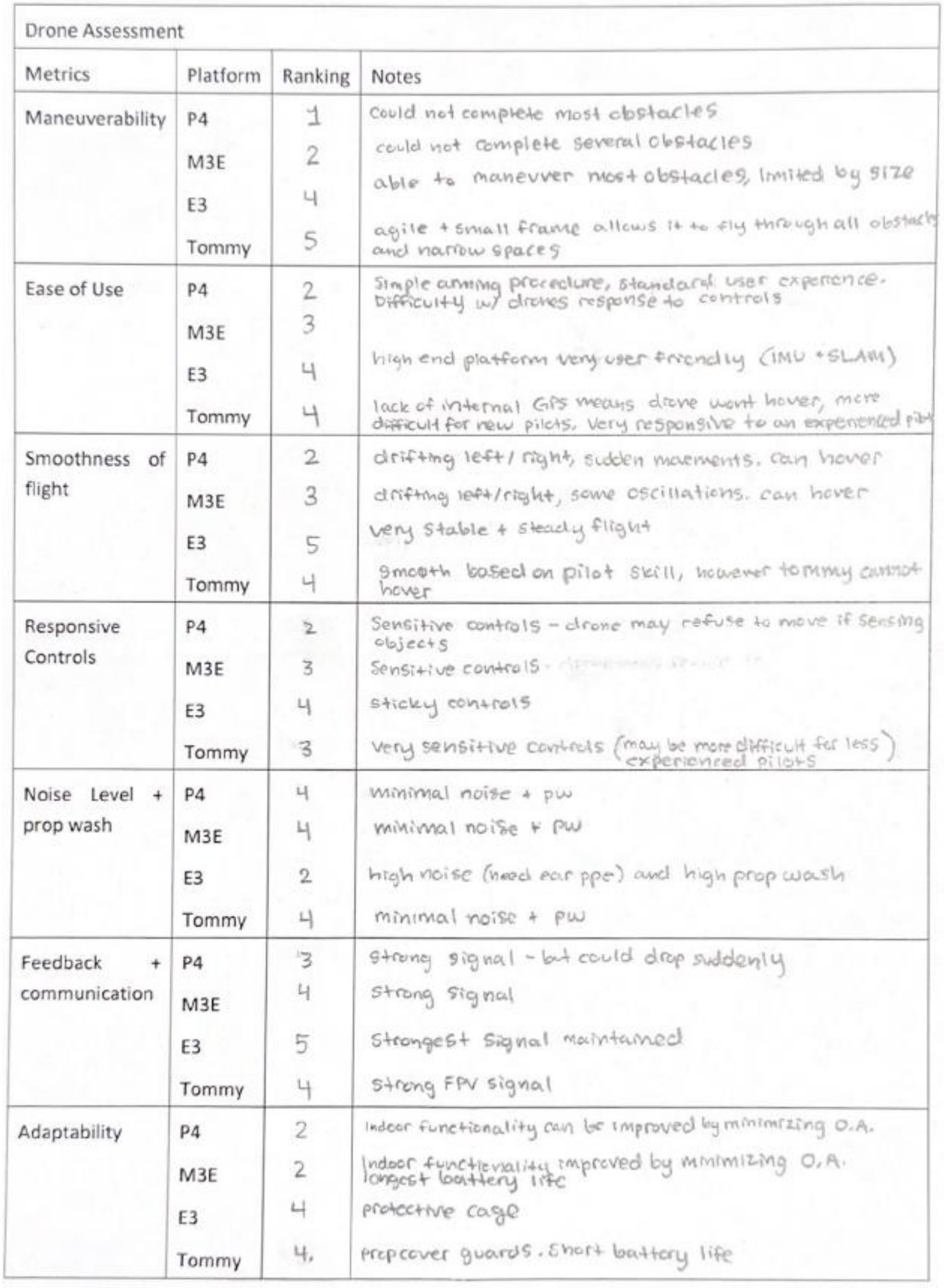
Platform	Sensor	Resolution
Tommyknocker	Main Camera	720 p 120 fps FPV feed Records in 1080p/60 fps
Phantom 4	Main Camera 1/2.3”	Video: 4k (4096 x 2160p at 25 fps) Photo: UHD 4k (3480 x 2160p at 30 fps)
Mavic 3E	L2D-20 C Aerial Camera	Video: 4k (4096 x 2160p at 120 fps) Photo: 20 MPS
Elios 2	Main Camera 1/2.3” CMOS Thermal Camera	Video: 4k UHD (3840 x 2160p at 30 fps) Photo: 1920 x 1080 at 30 fps 160 x 120p at 9 fps
Elios 3	Main Camera 1/2.3” CMOS LiDAR Ouster OS0-32 beams Thermal Camera	Video: 4k UHD (3840 x 2160p at 30 fps) Photo: 4000 x 3000p at 40 fps 2.6 MPS 160 x 120p at 9 fps
SPOT	SPOT CAM+	Video: 1080p Photo: 640 x 512p

5. Drone Performance Trials

Included in this chapter is a summary of the flight trials designed and implemented in indoor and underground environments. Although each UAV platform was designated to follow a similar course for each trial, there were slight variations. The chosen test environments include an indoor three-story building, an indoor tunnel setting, and the Orphan Boy underground Mine. A variety of trials were designed to test navigation, obstacle avoidance and maneuverability, signal integrity, and adaptability to dynamic operational conditions. Details of the trials are provided in the following sections. A full record of performance trial notes is provided in Appendix A: Performance Trials.

In order to accurately evaluate the performance of each platform, organization and documentation were key components. Task sheets were developed for each sequence of flight trials, covering information such as the platforms utilized, designated pilots, additional equipment or tools used, and an anticipated sequence of events and trial location. During each trial, detailed notes were taken which covered the specific flight trial conducted and the performance of each individual platform, being sure to detail important features such as adaptability and feedback noise with the controller.

In the assessment of each platform’s performance, a standardized evaluation process was developed to ensure consistency. An assessment sheet was crafted to systemically gauge each the performance of each platform, drawing from pilot feedback and firsthand observations. This assessment sheet was structured around essential criteria vital for successful drone operations, encompassing aspects such as maneuverability, ease of use, control responsiveness, smoothness of flight, noise level, feedback & communication, and adaptability. Each drone was assigned a ranking of 1 to 5 for each criterion for each series of flight trials, where 5 denotes an exceptional performance, 4 indicates above-average performance, 3 represents satisfactory performance meeting basic requirements but not having standout features, 2 indicates below-average performance with notable limitations in the specified variable, and 1 suggests poor performance. Figure 7 shows an example drone assessment sheet filled out for the indoor flight trials showing the metric being evaluated, the ranking for each platform, and a justification for the ranking.



Drone Assessment

Metrics	Platform	Ranking	Notes
Maneuverability	P4	1	Could not complete most obstacles
	M3E	2	could not complete several obstacles
	E3	4	able to manevver most obstacles, limited by size
	Tommy	5	agile + small frame allows it to fly through all obstacl and narrow spaces
Ease of Use	P4	2	Simple arming procedure, standard user experience. Difficulty w/ drones response to controls
	M3E	3	
	E3	4	high end platform very user friendly (IMU + SLAM)
	Tommy	4	lack of internal GPS means drone wont hover, more difficult for new pilots. Very responsive to an experienced pil
Smoothness of flight	P4	2	drifting left/right, sudden movements. can hover
	M3E	3	drifting left/right, some oscillations. can hover
	E3	5	very stable + steady flight
	Tommy	4	smooth based on pilot skill, however tommy cannot hover
Responsive Controls	P4	2	Sensitive controls – drone may refuse to move if sensing objects
	M3E	3	Sensitive controls
	E3	4	sticky controls
	Tommy	3	very sensitive controls (may be more difficult for less experienced pilots)
Noise Level + prop wash	P4	4	minimal noise + pw
	M3E	4	minimal noise + PW
	E3	2	high noise (need ear ppe) and high prop wash
	Tommy	4	minimal noise + PW
Feedback + communication	P4	3	strong signal – but could drop suddenly
	M3E	4	strong signal
	E3	5	Strongest Signal maintained
	Tommy	4	strong FPV signal
Adaptability	P4	2	Indoor functionality can be improved by minimizing O.A.
	M3E	2	Indoor functionality improved by minimizing O.A. longest battery life
	E3	4	protective cage
	Tommy	4.	propcover guards. Short battery life

Figure 7: Drone Assessment Sheet

5.1. Indoor Trial in the Mining & Geology Building

The indoor environment included a series of six trials. The location of the trials was the Mining & Geology Building on the Montana Technological University Campus which is a three-story building with a basement level. The floor plan design showing dimensions and annotated routes for the series of trials is provided in Figures 8, 10, 14, and 16.

5.1.1. Trial 1: First Floor Navigation Through Classroom & Hallways

The first flight trial sequence includes a loop through conjoined classrooms with both the lights on and off to assess drone lighting systems in low-light conditions, as well as exploration of the first-floor hallways to gauge the communications reliability of each platform around corners. The objective of this trial includes examining UAV obstacle avoidance systems to see if drones can fly through doorways ranging from 3' to 6' wide.

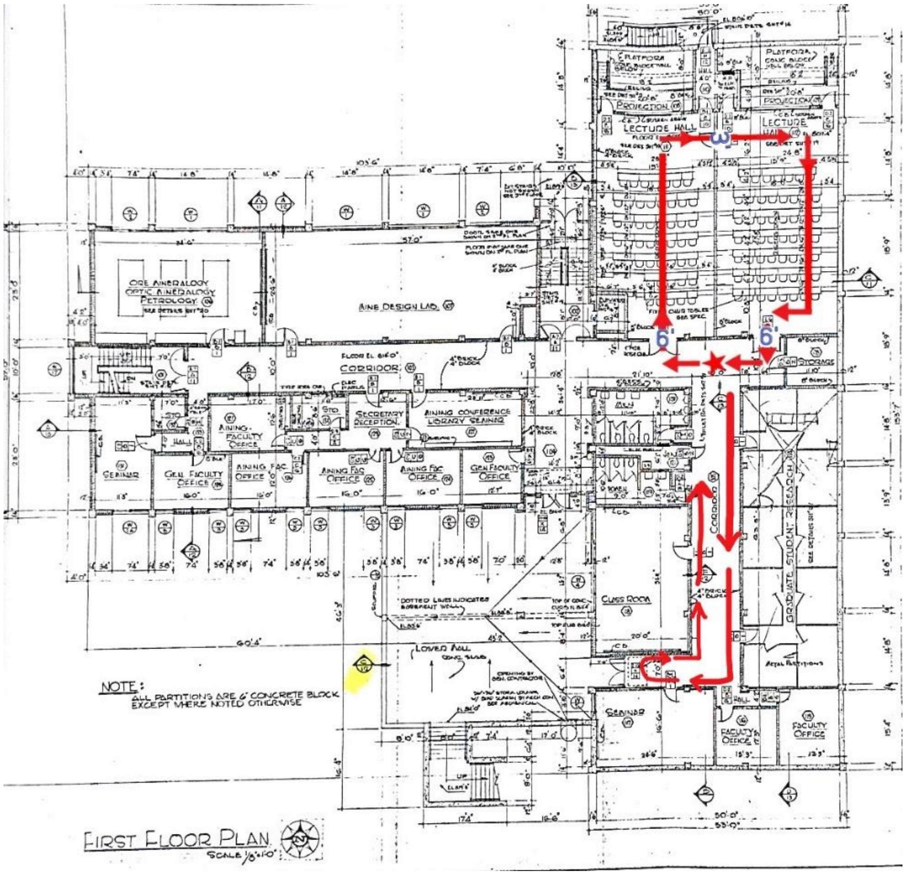


Figure 8: First Floor Navigation

The most challenging aspect for the Phantom 4 was maneuvering through narrow doorways. Its tendency to overcorrect and drift affected its performance during the loop through the classrooms. It was equipped with FoxFury lighting system, which provided significant illumination. Figure 9 shows a picture of the Phantom 4 UAV with the attached FoxFury lights. Despite the additional payload mass, pilot feedback suggested the FoxFury lights did not affect the stability of flight. The maneuvering difficulties during flight are likely attributed to collision avoidance systems. The Phantom 4 maintained consistent signal connectivity throughout the flight, demonstrating resilience in signal transmission.

Figure 9: Phantom 4 Equipped with FoxFury Lights

The Mavic 3E had difficulty navigating through doorways 6’ wide and required launching from within the classroom. Similar to the Phantom 4, it demonstrated sensitivity in controls, particularly evident with obstacle avoidance disabled. The Mavic 3E was also equipped with FoxFury lights. Despite limitations in tight maneuvers and drifting tendencies, the Mavic 3E maintained a strong signal connection during the entire flight duration.

In contrast to the other drones, the Elios 3 showcased remarkable stability and completed the loop through the conjoined classrooms with ease. Its flight down the hallway and around corners showcased its ability to navigate confined spaces effectively. Although encountering signal degradation around corners, the Elios 3 exhibited the ability to retreat to areas with stronger signal reception. The drone’s “sticky” controls contributed to its precision and minimized overcorrection during flight.

The Tommyknocker was able to successfully complete the loop through the classrooms and navigate down the hallways before experiencing pixelation in the signal. The drone has very responsive yet sensitive controls, and cannot maintain a stable hover independently from manual control. It relies heavily on an experienced pilot for a successful flight.

5.1.2. Trial 2: Second Floor Navigation Through Classroom Obstacles

For the second flight trial the mission was to navigate through obstacles in classroom MG 204 and complete a loop behind a brick wall along the north end of the classroom. The objectives for this trial are to assess signal integrity and communications systems behind a brick wall, as well as to examine drone maneuverability, obstacle avoidance, and ease of use. Figure 10 provides the annotated floor plan of the navigation route for the flight trial.

Figure 11 shows the layout of the lecture hall used for this flight trial, including the obstacle arrangement of stacked chairs at the front of the classroom. The Phantom 4 encountered significant challenges attempting to enter MG 204, failing to pass through the 3-foot-wide doorway. Despite utilizing obstacle avoidance systems, the drone still clipped the doorway when attempting entry. Within the main lecture hall area, the Phantom 4 could complete a loop around the room; however, it could not navigate between obstacles and was unable to enter the backroom, showcasing limitations in maneuverability and performance in confined spaces.

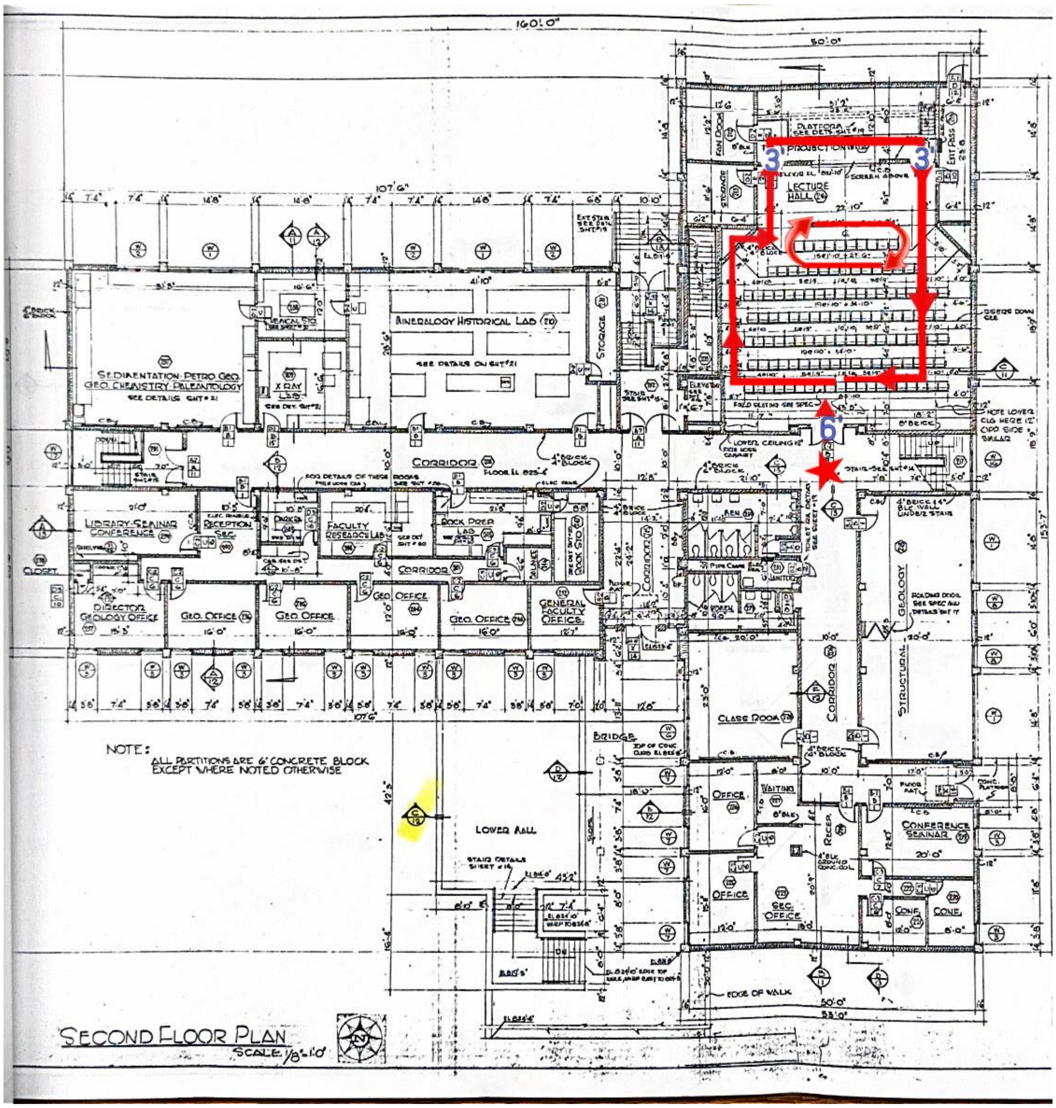


Figure 10: Second Floor Classroom Navigation

Figure 11: Lecture Hall Obstacle Set-up

The Mavic 3E also faced difficulties accessing the backroom. While able to complete a loop around the main lecture hall and perform basic maneuvers above obstacles, it lacked the agility to navigate between closely spaced obstacles due to obstacle avoidance sensors, resulting in limited maneuverability within the obstacle course.

The Elios 3 demonstrated exceptional performance by successfully navigating through the backroom while maintaining a strong signal behind the brick wall. This capability highlights the drone's effectiveness in environments with obstructive barriers. Within the main lecture hall, the Elios 3 displayed steady and controlled flight, maneuvering between obstacles without collisions. However, due to its larger size, it was restricted to flying through spaces wider than 1.5 feet, showcasing a limitation in tight maneuverability.

The Tommyknocker exhibited impressive maneuverability and agility, successfully accessing the backroom and maintaining signal integrity despite the brick wall barrier. In the main lecture hall, the drone expertly maneuvered through obstacles owing to its compact size and responsive controls. Despite lacking internal positioning sensors for hover stabilization, the Tommyknocker showcased rapid ground coverage and stability under skilled piloting. The Tommyknocker does have the most limited battery life of the four drones, up to about 5 minutes of flight time. However, it is also the fastest of all the drones, thus it is able to cover more ground in a shorter amount of time.

5.1.3. Trial 3: Second Floor Navigation Through Backroom Obstacles

The third flight trial included the development of an obstacle course in the MG 204 backroom, including hanging features, plywood barriers, pipes, and an A-frame ladder. This provided obstacles in a more confined space than the setup of obstacles in an open classroom.

This trial helped determine each platform’s limitations in confined spaces with obstacles. Figure 12 shows two photos which displays the arrangement of obstacles in the backroom of MG 204.

Figure 12: MG 204 Backroom Obstacle Set-up

The Phantom 4 and Mavic 3E were unable to enter the backroom due to obstacle avoidance sensors, and thus were unable to complete this flight trial. The Elios 3 showcased impressive maneuverability despite its size and the generation of prop wash (wind speed from propellers). It was able to successfully navigate all obstacles without knocking any obstacles over. The Tommyknocker excelled in navigating the obstacle course, and could fit through confined spaces and obstacles. Its compact size and agile controls allowed it to fit through tight spaces and complete the loop within the backroom with ease.

The Elios 2 and SPOT were tested through a limited variation of indoor scenarios due to testing delays. The first trial each drone was taken through was to complete the loop through the backroom of MG 204 with minimal obstacles (A-frame ladder). The Elios 2 experienced a 1 bar signal drop in the backroom, but successfully completed the loop and was able to maneuver under the ladder. Elios 2 performs very similarly to the Elios 3 in terms of responsiveness, maneuverability, and signal connectivity.

SPOT experienced no signal loss in the backroom of MG 204 and was able to navigate under the ladder. SPOT's maneuverability is limited by size; it is the largest of the platforms being tested. Its legs can get caught on obstacles, but SPOT is very hard to tip over. SPOT also demonstrated, if it ends up on its side or back, that it has the ability to right itself. SPOT was also able to open the door to the MG 204 lecture hall using its robotic arm.

Figure 13 shows SPOT's unique abilities such as opening doors with its robotic arm, and using its legs to flip itself back to an upright position after being put on its back. The controller can be used to adjust the sensitivity level of controls. Nearby signals (from active drones) can interfere with SPOT's connectivity. Feedback from the pilot suggests the controller for SPOT is intuitive and easy to learn. The controller also provides helpful feedback for the pilot such as warnings when signal is dropping or if moving objects are detected. SPOT is very stable due to being a walking robot and not airborne, giving the pilot more reaction time to determine course.

Figure 13: SPOT Opening Door & SPOT Flipped Over

5.1.4. Trial 4: Second Floor Hallway Navigation with Obstacles

The fourth flight trial focused on exploring the second-floor hallways and navigating through a series of obstacles, including a 3’ by 3’ PVC pipe cube, a sawhorse table approximately 2’ high, and two step ladders, meant to represent a 1’ obstacle in the space between two steps. The objective of this trial was to quantify the dimensions each platform could navigate through. Figure 14 shows the annotated layout of the flight trial route. Figure 15 shows the PVC pipe cube and the layout of the obstacles in the second-floor hallway.

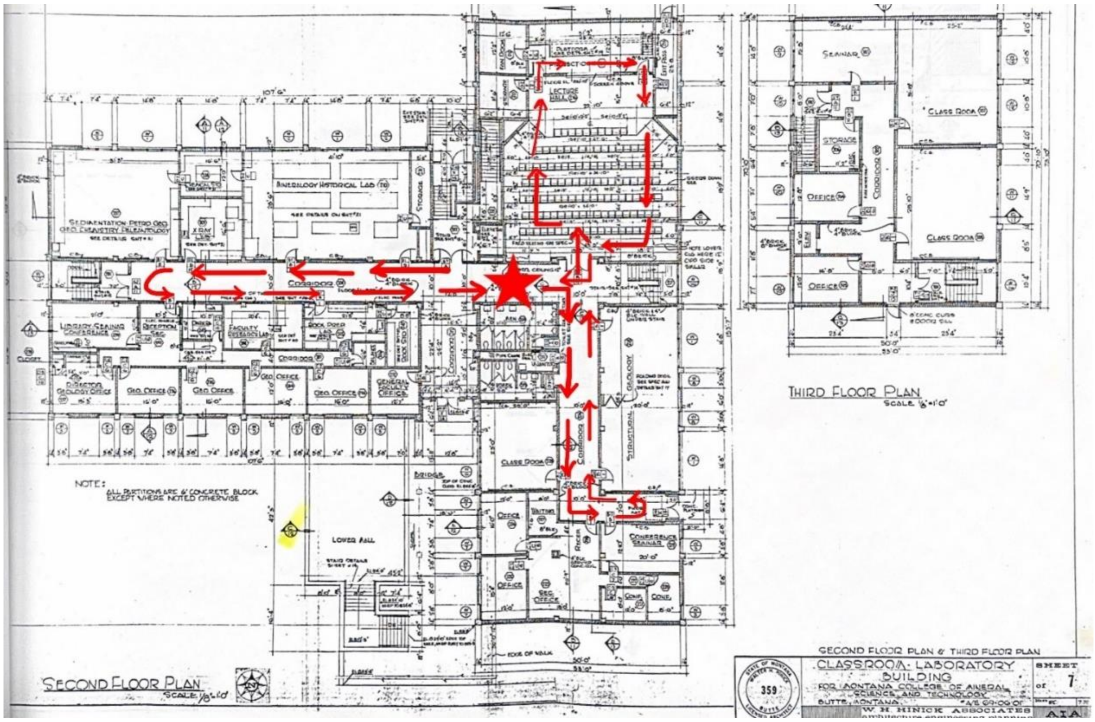


Figure 14: Second Floor Navigation

The Phantom 4 initially was resistant to maneuvering around or above obstacles and refused to fly forward. After setting obstacle avoidance settings to a minimum, the Phantom 4 showed improved performance. However, despite flying down the hallway above the obstacles, the drone could not navigate through them. Signal stability was maintained until approximately 10 feet around the corner, where the signal abruptly dropped, necessitating an emergency landing.

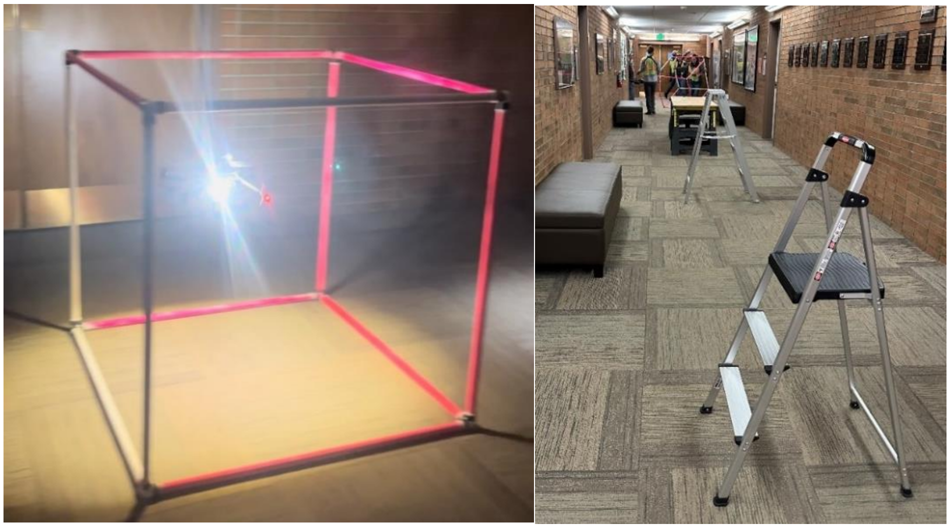


Figure 15: Second-Floor Obstacles

The Mavic 3E managed to fly through the 3’ wide PVC cube but struggled with other obstacles. Despite touchy controls and the tendency to drift, performance improved when obstacle avoidance settings were adjusted. The drone successfully navigated the hallway length and around the corner while maintaining a strong signal throughout the flight. The Mavic 3E displays the longest battery life of any of the four drones, managing to complete all flight trials without entirely draining one battery.

The Elios 3 exhibited adept obstacle navigation features, passing through the 3’ PVC cube and 2’ sawhorse table. However, it was too large to pass through the 1’ chair obstacle and had to navigate around it. Signal strength dropped to 2-3 bars around the corner but remained stable enough for the drone to navigate back through a different route (room MG 204) with a slight signal drop, ultimately returning successfully.

The Tommyknocker demonstrated exceptional performance by navigating through all hallway obstacles, including the 1’ chair, with ease. It successfully maneuvered down the hallway length and around the corner. Although the signal became pixelated when flying into MG 204 and the backroom, it did not significantly drop, showcasing resilience in maintaining connectivity.

The Elios 2 was able to maneuver through the 3’ PVC cube and under the 2’ tall sawhorse table, and was able to fly under the step ladder. SPOT is restricted by size and could only maneuver through the PVC cube and around the other obstacles.

5.1.5. Trial 5: Multi-Floor Navigation

The fifth flight trial involved navigating multiple floors through stairwells and hallways. Thes objective of this trial was to determine signal integrity and communications across multiple floors and beyond line-of-sight operations. Figure 16 shows the annotated route for the flight trial. Red arrows show the descending path, and blue arrows show the ascending path.

Neither the Phantom 4 nor Mavic 3E attempted the trial due to obstacle avoidance sensors preventing safe descent down the stairwell. The drones were restricted from initiating the mission due to safety concerns.

The Elios 3 exhibited impressive performance by starting on the second floor and descending the stairwell to the first floor. It then navigated down the first-floor hallway, ascending another stairwell back to the second floor, completing a loop. Throughout this sequence, the drone maintained strong signal and stable flight. Subsequently, the Elios 3 descended from the second floor to the first floor and further down to the basement level, navigating the basement hallway and returning via another stairwell. Although the signal dropped to 1 bar during this phase, the drone successfully completed the loop.

Similarly, the Tommyknocker successfully flew from the second floor to the first floor, down the hallway, and back up another stairwell, completing a loop. The drone maintained strong signal and stable flight throughout this sequence. However, when attempting to descend to the basement level, the signal dropped significantly, and the pilot abandoned the mission to avoid losing the drone.

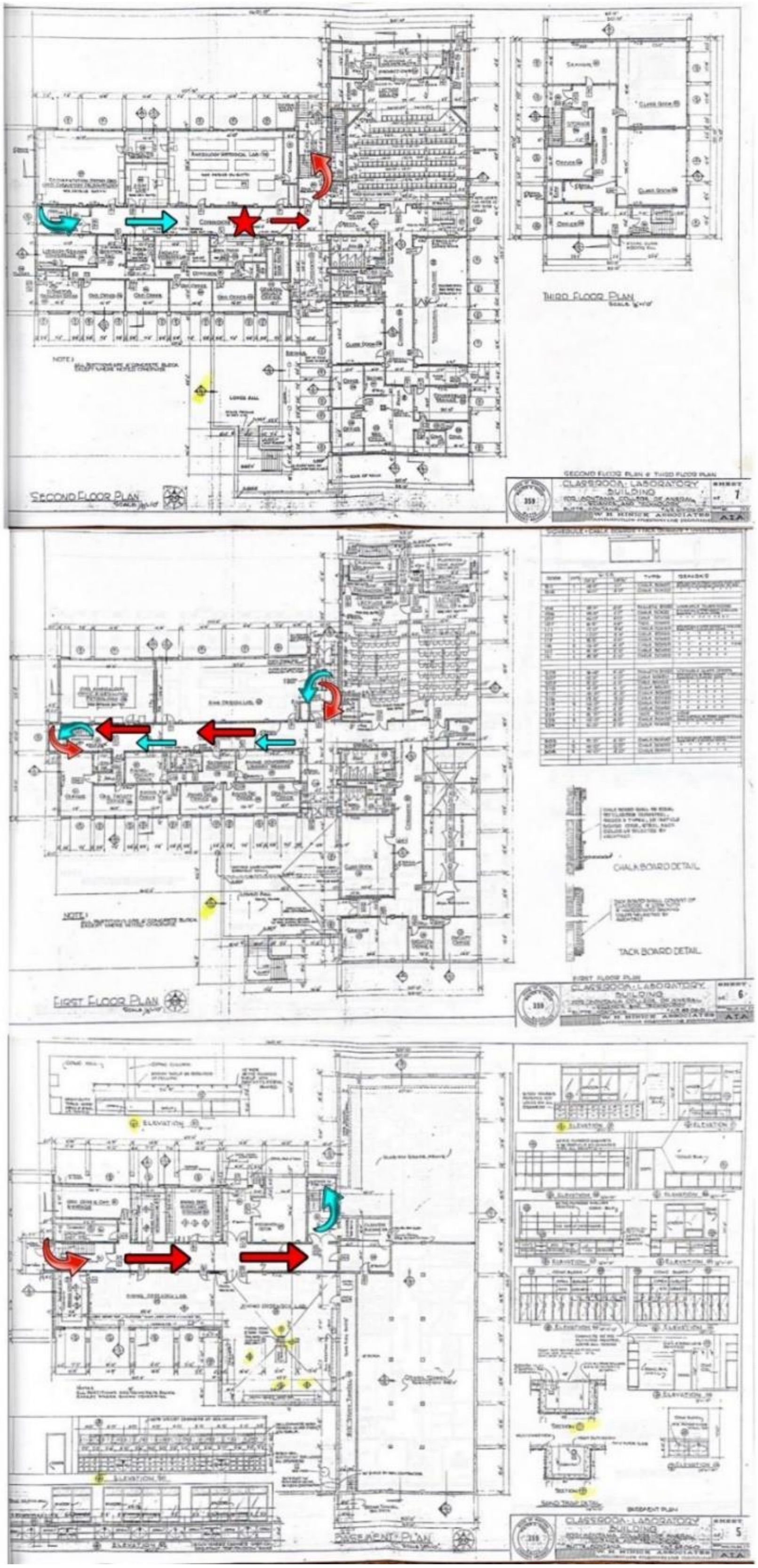


Figure 16: Multi-Floor Navigation

The Elios 2 successfully completed a multi-floor loop from the basement level to the first level and then to the second level and back down to the basement. It experienced signal interference in the basement stairwell but recovered and was able to return to the pilot. Figure 17 shows the Elios 2 descending down the stairwell. SPOT started at the basement level by the stairwell and made it to the first-floor level and approximately 10 ft down the hallway before losing signal. The pilot moved partially into the stairwell to attempt to regain signal and was able to reconnect with SPOT and guide the robot back down the stairs.

Figure 17: Elios 2 in Stairwell

5.1.6. Trial 6: Elevator Descent

The sixth and final flight trial was only performed by the Elios 3. The final trial was to fly the drone into an elevator and descend one floor within the elevator and then to navigate through the hallways and up a stairwell back to the staging area. This trial examined the internal positioning system of the platform as well as signal integrity. The Elios 3 successfully completed this mission, and maintained a hover while inside of the elevator due to onboard IMU positioning.

5.2. Indoor Tunnel Trial

The indoor tunnel used for these trials is located underneath the Science & Engineering building and the Main Hall building on the Montana Tech campus. A reference sketch of the dimensions of the tunnel is Shown in Figure 18.

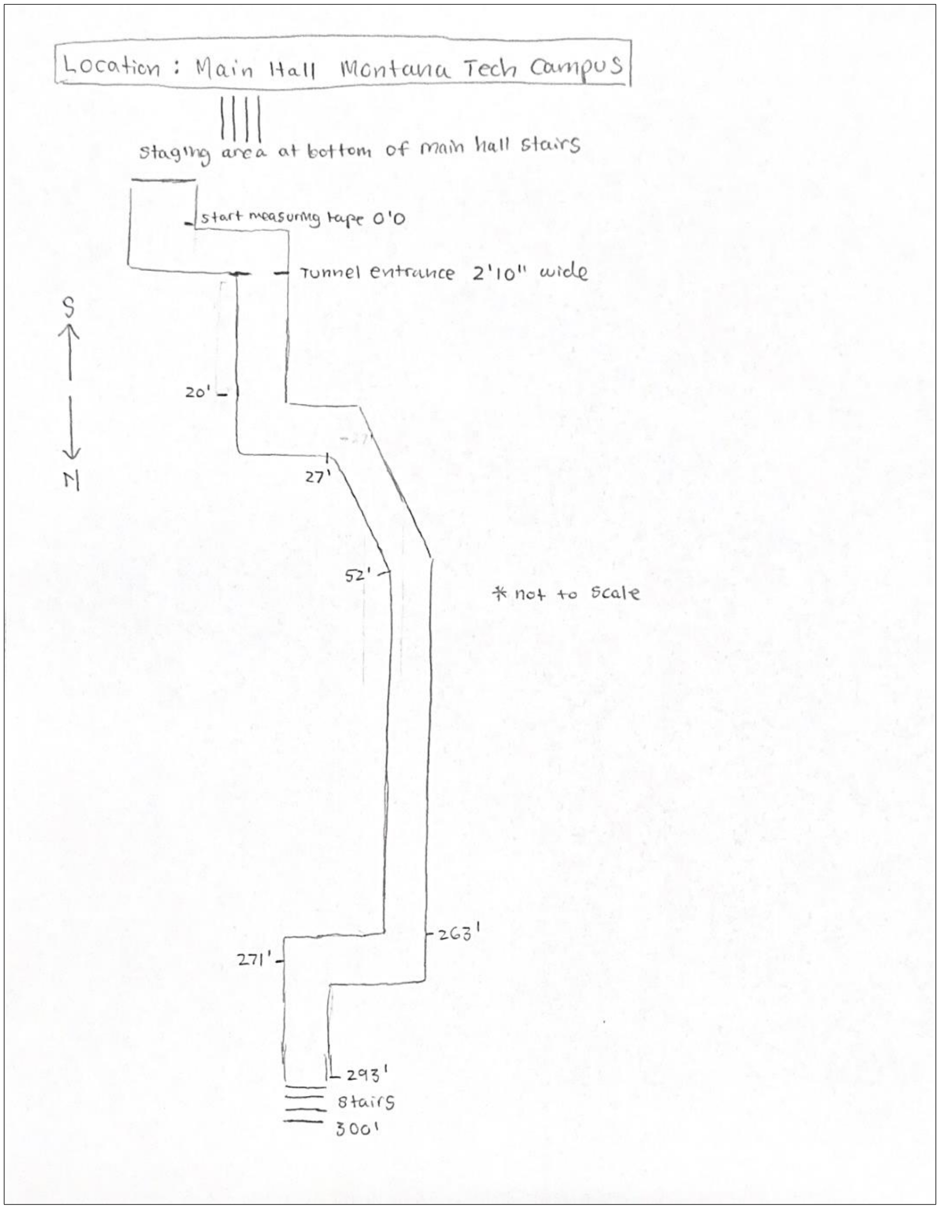


Figure 18: Indoor Tunnel Layout Reference

The Elios 3 was not available during the tunnel performance trial; however, it was established from the indoor trials that the Elios 2 and the Elios 3 have comparable performance.

The tunnel is approximately 300’ long, with several turns which limits line-of-sight piloting. The entrance to the tunnel was measured as 2’10” wide. Once inside the tunnel, it widens to around 4’, however there are pipes running along the wall which narrows the width of accessible space.

The Phantom 4 was able to take off in the staging area but could only fly briefly down the hall before stopping and becoming frozen; it was unresponsive to any controls the pilot attempted. Eventually the pilot forced a landing, and the mission was abandoned due to the Phantom 4 being unable to navigate the hallway. This is likely due to its obstacle avoidance sensors conflicting with the narrow dimensions of the tunnel staging area.

The Tommyknocker was only able to navigate 10’ past the first corner before losing signal completely and the drone crashed. The pilot attempted to regain signal by moving closer to the drone, however the drone refused to take off due to unstable signal. The flight was attempted again with the pilot standing at the entrance of the tunnel. The Tommyknocker made it to the 259’ distance on the measuring tape.

SPOT made it to the 28’ mark on the measuring tape (around the first corner) before losing signal. The pilot re-stationed at the entrance of the tunnel and SPOT was able to make it to the 95’ mark. Figure 19 shows a photo of SPOT walking down the length of the tunnel. The pilot re-stationed once again at the 51’ mark, and SPOT was able to reach the 238’ mark before losing signal. Prior to losing signal completely, SPOT started staggering while walking as the signal dropped. SPOT automatically sits down when the signal is completely lost. The pilot attempted to regain signal by moving towards SPOT. The signal was regained at the 157’ mark. SPOT had difficulty making a 180 degree turn in the confined tunnel, the pilot was able to turn off obstacle avoidance and SPOT was able to make the turn and return to the pilot.

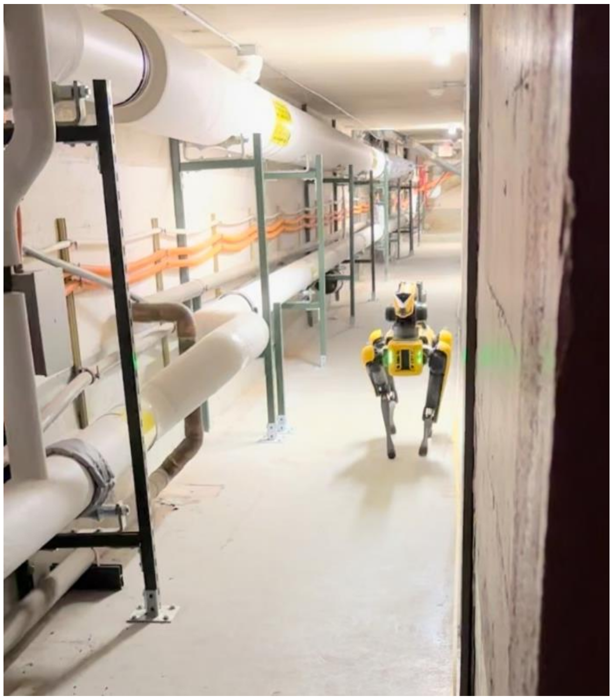


Figure 19: SPOT in Indoor Tunnel

The Mavic 3E could not make it around the first corner, even with obstacle avoidance set to minimums. The drone was frozen and hovered in the air. The pilot was able to land the drone and try to take off again, and could navigate around the first corner by strafing the drone instead of yawing. Yawing is when the face of the drone turns, strafing is when the drone moves side to side without turning. The Mavic 3E made it to the 26' mark, but was unable to enter the tunnel due to the narrow entryway.

The Elios 2 was able to take off from the staging area and navigate through the entryway into the tunnel. The Elios 2 stirred up significant dust from prop wash and ultimately set off the fire alarm at the 190' mark in the tunnel due to too much dust triggering the alarm. The mission was abandoned at that point, and all pilots and spotters evacuated the tunnel. Despite the abrupt end to the performance trial, each platform was able to demonstrate its abilities with signal range and limitations with confined spaces.

5.3. Underground Mine Trials

The final performance assessment took place at the Montana Tech Underground Mining Education Center (UMEC) – located in the Orphan Boy Mine – with an entrance based southwest of the Montana Tech campus. A map of the drift systems within the UMEC is available in Figure 20. The dimensions of the drifts are approximately 12x10 feet, but can vary across different adits due to changes in rock stability and active excavations.

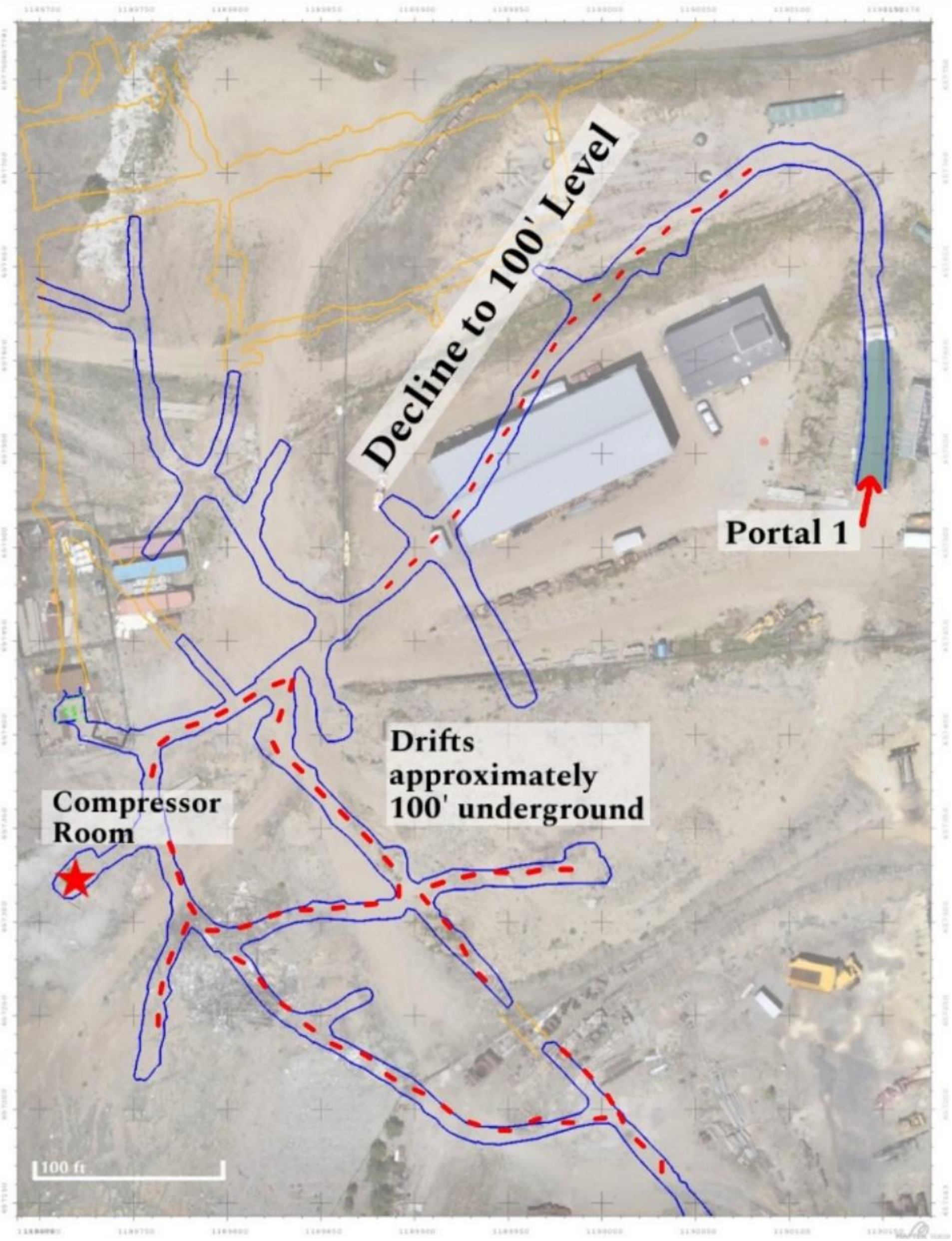


Figure 20: UMEC Map

The first trial was to stage outside of the mine entrance and test each platform’s ability to fly into the mine from the opening, and then test whether the drone can take off and land from within the mine. The objectives for this trial were to assess each platform’s ability to fly into and from within a mine adit. The second trial examined the signal range of each drone from the pilot stationed at the mine entrance, examining communication reliability. The third trial was staged from the compressor room in the mine, and multiple flight sequences were conducted at this location. These series of flights examined a platform’s ability to fly around a mine pillar, focusing on signal range. There was significant dust and some water droplets so the performance of each drone was able to be assessed in regard to these hazards looking at visibility and reliability. Additionally, signal range was again explored by navigating the platforms down a straight drift for as far as the drone could maintain communication with the pilot.

5.3.1. Trial 1: Staging Outside of the UMEC

The first trial was to stage outside of the mine entrance and test each platform’s ability to fly into the mine, and then test whether the drone can take off and land from within the mine. Figure 22 shows the annotated layout of flight trial 1. Figures 22 and 23 show each pilot staging outside of the UMEC.

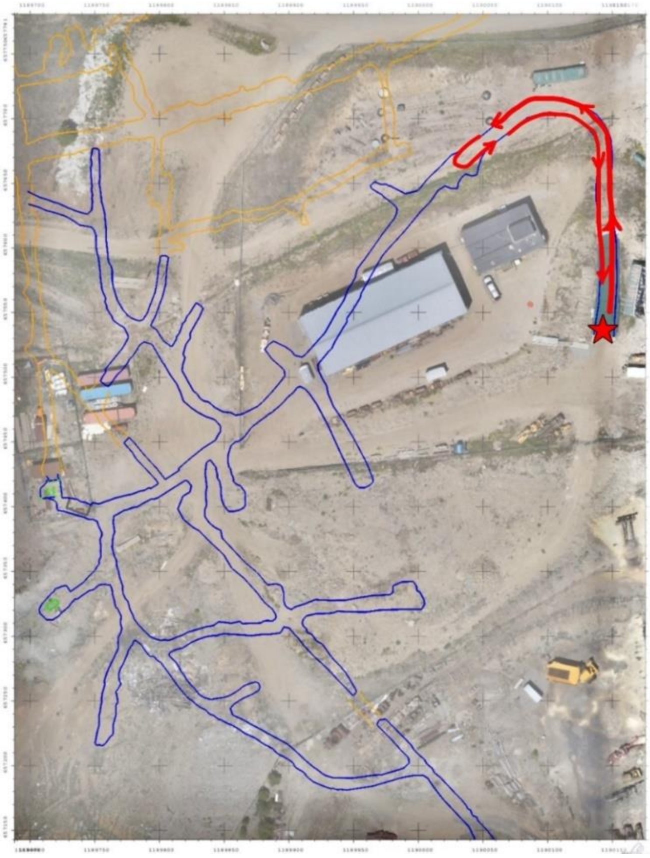


Figure 21: Staging Outside of the UMEC

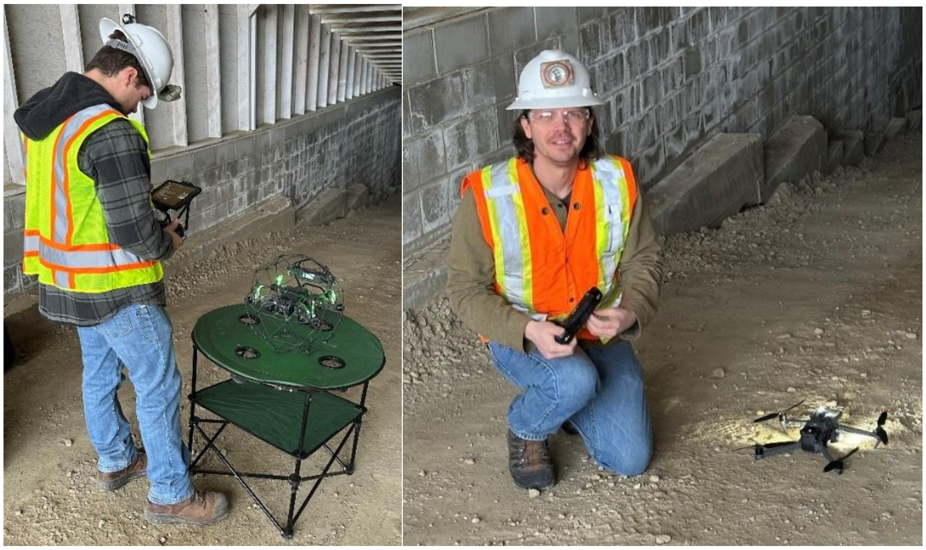


Figure 22: Karl Farber Piloting Elios 2 & Chris Langhoff Piloting Mavic 3E

Figure 23: Rusty Turner Piloting Elios 3, Jim Jonas Piloting Tommyknocker, & Kodis Campbell Operating SPOT

The Phantom 4 kicked up significant dust from prop wash and had visibility issues from the resulting dust cloud. It was able to successfully fly into the mine from outside of the mine; and it was also able to take off and land from within the mine itself. The Tommyknocker produced only a minimal dust cloud and it was able to fly into the mine tunnel from outside, and was able to take off and land from within the tunnel. The Mavic 3E was also successful in entering the mine from the outside, as well as taking off and landing from within the mine. The

Mavic 3E produced a dust cloud. SPOT was able to walk into the mine from outside of the entrance, as well as start/stop from within the mine. The Elios 2 produced a significant dust cloud but was able to enter the mine from the outside and take off and land from within the mine. The Elios 3 performed similarly, but rolled upon landing in the mine due to the spherical structure of the drone's protective cage and the slope gradient of the adit.

5.3.2. Trial 2: Signal Range Near the UMEC Portal

The second trial examined the signal range of each drone from the pilot stationed at the mine tunnel entrance. The flight paths consisted of a decline with a 15% grade and a sharp curve which preventing line-of-sight flying, shown in Figure 24. The star indicates the starting point for all the platforms. The solid line shows the initial flight trajectory around the curve which all platforms were able to initiate. The dotted line indicates the furthest trajectory taken by only the platforms that were able to maintain connection with the pilot.

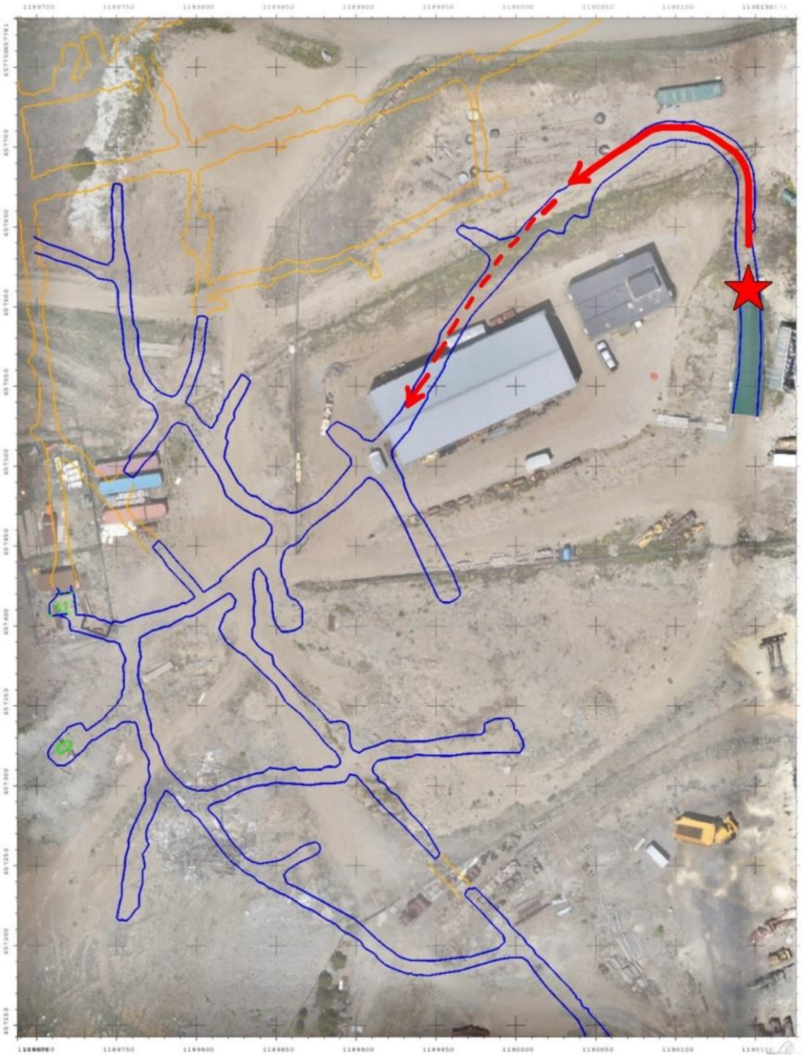


Figure 24: Staging Within the UMEC

The Phantom 4 was maintaining a decent signal with the pilot as it flew into the mine, however, due to the dust cloud it crashed at 122’ due to lack of visibility. The Tommyknocker also reached 122’ from the entrance of the mine, which is around the first corner. It performed an emergency landing once the signal dropped, and could not re-arm even when the pilot moved closer, so it had to be carried out of the facility. The Mavic 3E gained significant stability in its performance within the mine as compared to its performance indoors, likely due to higher ceilings and a wider tunnel thus not interfering with its obstacle avoidance sensors. The Mavic 3E maintained full signal around the first corner, but seemed to start drifting more the further it flew from the pilot. It landed at 1 bar of signal at 303’. The pilot was able to re-arm the drone and fly out of the mine from where it landed. SPOT lost signal at 125’ from the mine entrance. The auto-return feature was tested out and was successful – once SPOT lost connection it walked back in order to reestablish communications. The Elios 2 reached 309’ and rolled upon landing due to the gradient and the spherical nature of the protective cage around the drone. This is similar to the performance of the Elios 3, whose distance was not established due to rolling from its landing point, but reached at least 309’.

5.3.3. Trial 3: Navigation Around a Mine Pillar

The third trial staged from the compressor room in the mine, and multiple flight sequences were conducted at this location including attempted navigation around a mine pillar with an approximate perimeter of 300’ (depicted in red in Figure 25). As well as beyond line-of-sight flying up the decline (depicted in purple in Figure 25) which covered a length of over 200’.

During the attempted flight around the pillar, the Phantom 4 exhibited poor control and was unstable. It crashed 65’ from takeoff point and was not able to make it around any of the corners of the mine pillar. The Mavic 3E lost vision positioning due to lighting being too low (even with the FoxFury light attachments). The N mode positioning engaged after takeoff. The signal was strong until about 300’ from takeoff point and then dropped to 1 bar. It started to initiate an emergency landing but signal strengthened again enough for the pilot to return the drone to home.

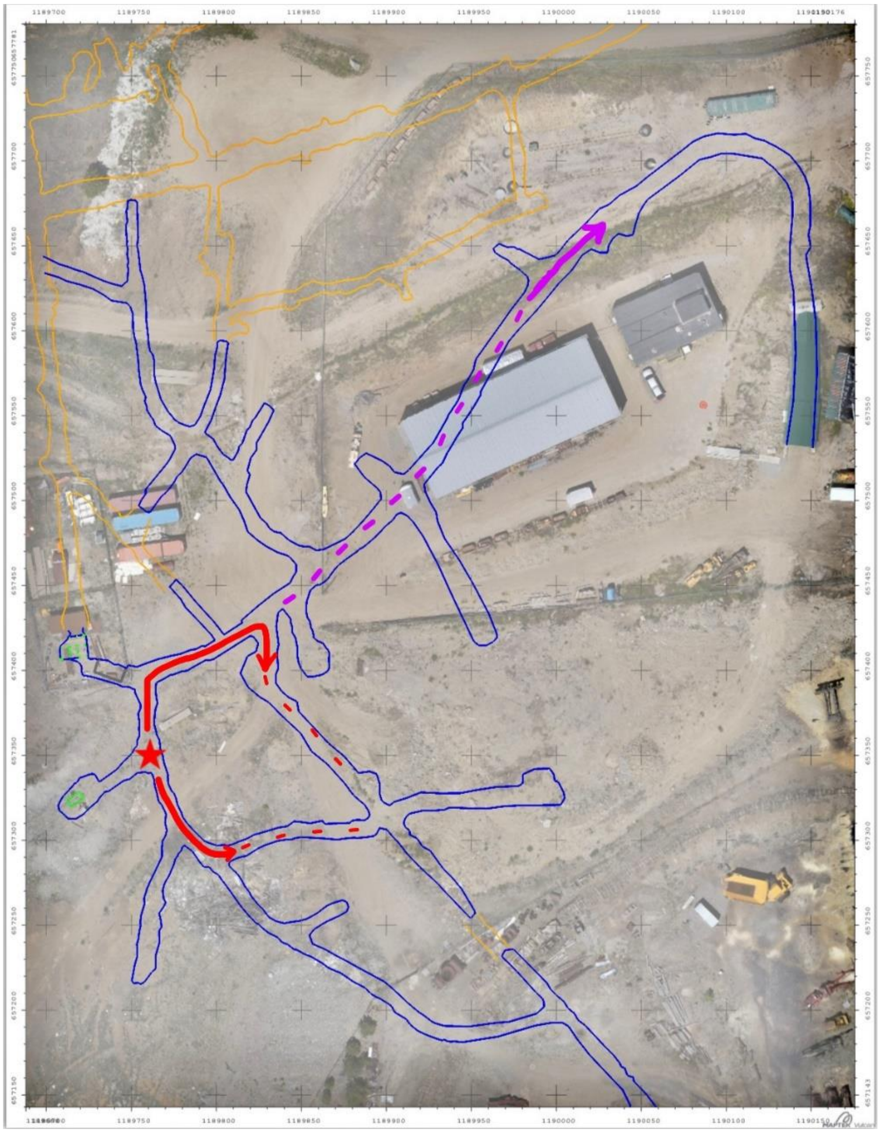


Figure 25: Trial 3 Navigation Sequence

The Mavic 3E maintained stable flight and control. The next attempt was to try to fly a loop around a mine pillar; it made it around the first corner and almost to the second corner, but had to return to home due to the presence of a mine mucker obstacle. The loop was attempted again going the other direction around the mine pillar, and the Mavic 3E made it around the second corner before losing signal. It was not able to successfully navigate a complete loop around the mine pillar. The final sequence was to fly the straight away heading to the primary exit of the mine. The signal was lost close to the exit. The Mavic 3E demonstrated the strongest signal connection out of any of the platforms, and it also exhibited the second longest battery life after SPOT.

The Elios 2 reached 227’ distance when flying the straight away, but started to receive weak signal warnings before the signal dropped completely. On the mine pillar attempt, the Elios 2 made it around the first corner before losing signal. Figure 26 shows the dust cloud generated by the Elios 2 upon takeoff. The Elios 3 performed slightly better and reached 254’ distance from the staging area and had to land due to signal loss. On the mine pillar attempt, the Elios 3 made it around the first corner and almost to the second corner before losing signal. Figure 27 shows the Mavic 3E and Elios 2 staged at the compressor room.

Figure 26: Elios 2 Dust Cloud

The Tommyknocker reached 260’ distance when flying the straight away but crashed when signal was lost, not enduring any noticeable damage to the platform or propellers. The mine pillar loop was attempted going both directions around the pillar. The Tommyknocker made it just past the second corner before losing signal on both attempts. SPOT made it 68’ from the pilot. The pilot re-stationed at the straight away to maintain line-of-sight with SPOT, and the robot was able to make it 126’ distance. SPOT was able to hold a mine headlamp in its arm claw to provide further illumination than its onboard flashlight. On the mine pillar loop attempt, SPOT could only navigate around the first corner before losing signal.

Figure 27: Mavic 3E (Left) and Elios 2 (Right) Staged at the Compressor Room

5.4. Summary of Performance

The series of trials in the underground mine setting of the UMEC demonstrated varied performances among the platforms. SPOT had the best overall battery life and stability, though its signal range was mostly limited to line-of-sight operations. The Mavic 3E exhibited the second longest battery life and excelled in signal range, outperforming even the Elios 3. The Elios 2 and Elios 3 showed strong stability, with the Elios 3 slightly ahead in terms of signal range. The Tommyknocker had decent signal range but posed a risk of crashing abruptly if signal dropped, not having the ability to initiate an autonomous return to home or emergency landing like higher end platforms. The Phantom 4 generated substantial dust clouds from prop wash, severely limiting visibility. It also demonstrated poor stability, making it unsuitable for use in confined spaces. These trials highlight the importance of a responsive platform with the ability to adapt to changing environments and space restrictions.

Table IX summarizes the signal range beyond line of sight each platform could reach, and the minimum dimensions of navigable obstacles. These variables were tested in the field throughout the series of performance trials, and reflect the capabilities of each platform under various environmental conditions. The data provides a comprehensive overview of how well each platform can maintain communication and maneuverability when faced with real-world challenges. These results are critical for assessing the practical applications and limitations of the platforms. From the performance trials it was determined that the Tommyknocker, Elios 2, Elios 3, and SPOT can pass through and around objects that are at a minimum greater than the platform’s own dimensions. The Mavic 3E is constrained to a minimum passable dimension of 3 feet, and the Phantom 4 cannot pass through objects or spaces with dimensions smaller than 6 feet. The signal range for each platform is based on recorded measurements from the performance trials discussed in sections 5.1 to 5.3; however, signal range can be significantly affected by the thickness and composition of obstructions between the pilot and the platform, which may reduce or increase the effective range. Thicker materials, such as metal or solid rock, tend to attenuate the signal more than thinner or less dense materials like drywall.

Table IX: Summary of Signal Range & Obstacle Dimensions

Platform	Signal Range Beyond Visual Line-of-Sight (feet)	Minimum Dimensions of Navigable Obstacles (feet)
Tommyknocker	122	.4
Phantom 4	65-122	6
Mavic 3E	≈400	3
Elios 2	309	1.5
Elios 3	309	1.5
SPOT	28-68	1.6

6. Drone Assessment Results and Discussion

In conclusion, the analysis of drone performance in GPS-denied environments reveals a clear stratification based on technological sophistication and design intent. Highly advanced drones like the Elios 2 and Elios 3, built for the purpose of operating in GPS-denied settings, demonstrate superior performance across various metrics. Their advanced sensor suites and navigation algorithms enable precise maneuverability and reliability in challenging conditions. They are operationally easy to use and can hover in place, allowing a pilot to focus on slow and steady maneuvering through confined spaces without worry of crashing. However, this high level of performance comes at significant cost, making them an investment primarily justifiable for specialized applications.

Similarly, SPOT the four-legged robot has an intuitive controller system which allows for easy operation. It has unique features like the extendable arm which can open doors or pick up small objects. SPOT displayed the poorest signal range of all the platforms tested, and can primarily only be used in line-of-sight operations; there are possible signal range extender upgrades for the robot, at additional cost. SPOT is able to maneuver through confined spaces, but is limited by its large size. In addition, SPOT cannot provide support for aerial applications as it is a walking robot, and it cannot assist with deploying a UAV due to signal interference between platforms. This platform would be best suited for specialized ground applications where the operator can maintain line of sight.

On the other end of the spectrum, custom built drones with minimal sensor packages - like the Tommyknocker - also perform well in GPS-denied environments, particularly in confined spaces. Their limited sensor arrays reduce the likelihood of interference and facilitate smoother operation in restricted areas. Although the lower resolution camera quality limits the use for mapping and detailed inspections, they can still be used as a reconnaissance tool for many applications. A custom-built drone likely does not have an internal positioning system; thus the drone cannot hover in the place and the operator must be constantly piloting the drone. The successful completion of a mission depends in large part on the skills of the pilot. The Tommyknocker has the shortest battery life of all the platforms tested, but due to its compact build and the fastest speed of the drone selection, it can cover the most ground in the shortest timespan while also fitting in the most restricted areas. Due to the low cost of the platform, it could also be a good choice for use in high-risk areas such as down mine shafts or unstable underground areas. This makes them a cost-effective alternative for specific use cases where simplicity and adaptability are prioritized.

Conversely, mid-level drones which are not specifically designed for indoor and GPS-denied applications, such as the Phantom 4 and - to a slightly lesser extent - the Mavic 3E, exhibit the poorest performance in these environments. The sophisticated obstacle avoidance sensors that are advantageous in open or outdoor settings tend to restrict their movement in confined spaces, leading to suboptimal performance. While these drones did display longer battery life and advanced camera resolution, their ability to fly in confined spaces is severely restricted. This indicates a mismatch between their general-purpose design and the specific demands of GPS-denied environments.

Table X shows the overall assessment ratings of how each platform performed with respect to the criteria evaluated. Each platform was given a ranking based on a combination of direct observations and pilot feedback collected during the flight trials. Pilots provided detailed feedback on their experience operating their designated UAV or robotic platform. They commented on aspects such as ease of use, control responsiveness, and overall satisfaction with the drone’s performance. During the performance trials, observations were made to assess each platform taking note of any issues or exceptional performances related to maneuverability, smoothness of flight, and adaptability. Drone communications are based on the measured signal range of each platform in the field. Based on the collected feedback and observations, each criterion was assigned a ranking from 1 to 5, with 1 being the poorest performance and 5 denoting an exceptional performance.

Table X: Drone Assessment Ratings (5=excellent, 1=poor)

Platform	Maneuverability	Ease of Use	Responsive Controls	Smoothness of Flight	Communication	Adaptability
Tommyknocker	5	4	3	4	4	4
Phantom 4	1	2	2	2	3	2
Mavic 3E	2	3	3	3	5	2
Elios 2	4	4	4	5	4	4
Elios 3	4	4	4	5	5	4
SPOT	5	4	3	4	4	4

Overall, the study highlights the importance of matching drone capabilities to operational requirements, with both highly specialized and simple platform solutions proving effective under the right conditions, while general-purpose drones may struggle in more complex and dynamic GPS-denied environments. Table XI breaks down the main advantages and disadvantages of each platform, taking into consideration the potential various use cases for which they might be employed. The detailed comparison helps to identify the strengths and weaknesses of each platform, guiding users in selecting the most appropriate platform for a specific need.

Future research can expand on this topic by including more platforms in the study pool. Additional flight trials could cover various real-world simulations such as a mine-based search and rescue. A fog machine could create a low visibility environment similar to smoke, and a mannequin or other prop could be placed within a mine adit. Each platform could be tested on the ability to navigate through fog and identify the location of the subject prop in a timely manner. Another challenge to be included in further studies could be the use of fans to simulate wind and turbulence, allowing observations of how well the platforms maintain stability in adverse conditions. Repeating earlier trials using a broader range of platforms can help highlight what features are desirable and what features might restrict the functional use of a platform in indoor and underground environments.

Table XI: Summary of Platform Advantages & Disadvantages

Platform	Advantages	Disadvantages
Tommyknocker	Compact size, high speed capabilities, low cost, can be customized with preferential batteries/lights, protective barrier around propellers, strong signal range	Lower resolution camera, not pre-constructed, no IMU (cannot hover independently), high noise level (>80 dB)
Phantom 4	Moderate cost, high resolution camera, contains an IMU, long battery life	Unprotected propellers, sensitive obstacle avoidance sensors, high noise level (>80 dB)
Mavic 3E	Moderate cost, high resolution camera, contains an IMU, strong signal range, long battery life	Unprotected propellers, sensitive obstacle avoidance sensors, moderate-high noise level (>70 dB)
Elios 2	High resolution camera, protective carbon fiber cage, contains an IMU, strong signal range, stable flight patterns	High cost, very high noise level (>90 dB)
Elios 3	High resolution main camera, thermal camera, and LiDAR unit, protective carbon fiber cage, contains an IMU, strong signal range, stable flight patterns	High cost, high noise level (>80 dB)
SPOT	Extendable arm, easy to operate, low noise level (<70 dB), long battery life	High cost, no aerial feature, large dimensions, low speed capabilities

This study did not evaluate the functionality of autonomous flight capabilities, which refers to the capabilities of a UAV to operate without direct human operation. Evaluating these advanced systems was beyond the scope of this study due to the lack of access to these expensive tools and a decision to focus on manual operation. However, autonomous flight technology is an emerging field that is expected to see increased use across various applications as costs come down over time. Future research should consider including more platforms with autonomous flight capabilities and focus on their practical applications to provide a more comprehensive assessment of unmanned platforms in evolving operational contexts.

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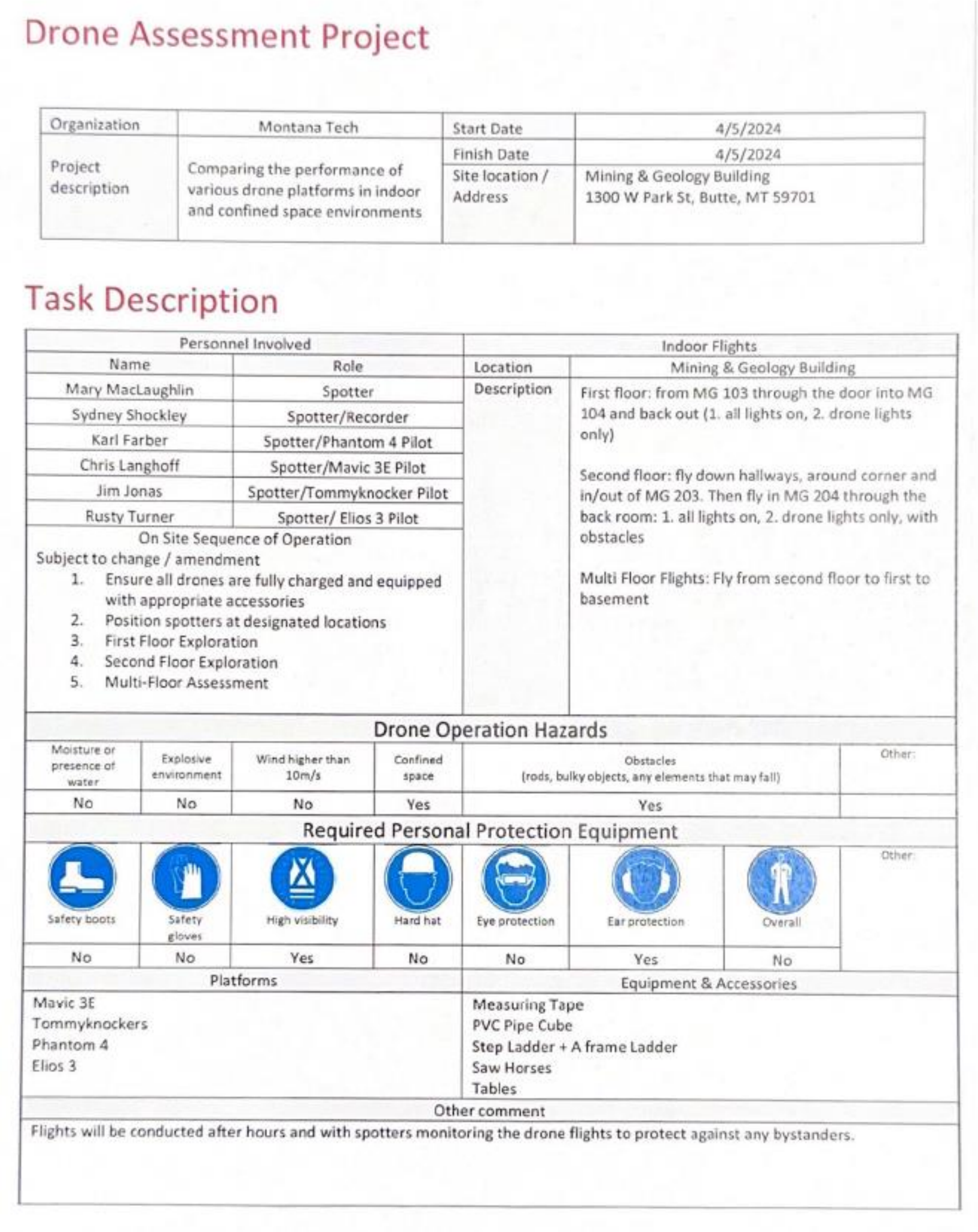
Appendix: Performance Trial Notes



Drone Assessment Project

Organization	Montana Tech	Start Date	4/5/2024
Project description	Comparing the performance of various drone platforms in indoor and confined space environments	Finish Date	4/5/2024
		Site location / Address	Mining & Geology Building 1300 W Park St, Butte, MT 59701

Task Description

Personnel Involved	
Name	Role
Mary MacLaughlin	Spotter
Sydney Shockley	Spotter/Recorder
Karl Farber	Spotter/Phantom 4 Pilot
Chris Langhoff	Spotter/Mavic 3E Pilot
Jim Jonas	Spotter/Tommyknocker Pilot
Rusty Turner	Spotter/ Elios 3 Pilot

On Site Sequence of Operation

Subject to change / amendment

1. Ensure all drones are fully charged and equipped with appropriate accessories
2. Position spotters at designated locations
3. First Floor Exploration
4. Second Floor Exploration
5. Multi-Floor Assessment

Indoor Flights	
Location	Mining & Geology Building
Description	First floor: from MG 103 through the door into MG 104 and back out (1. all lights on, 2. drone lights only) Second floor: fly down hallways, around corner and in/out of MG 203. Then fly in MG 204 through the back room: 1. all lights on, 2. drone lights only, with obstacles Multi Floor Flights: Fly from second floor to first to basement

Drone Operation Hazards

Moisture or presence of water	Explosive environment	Wind higher than 10m/s	Confined space	Obstacles (rods, bulky objects, any elements that may fall)	Other:
No	No	No	Yes	Yes	

Required Personal Protection Equipment

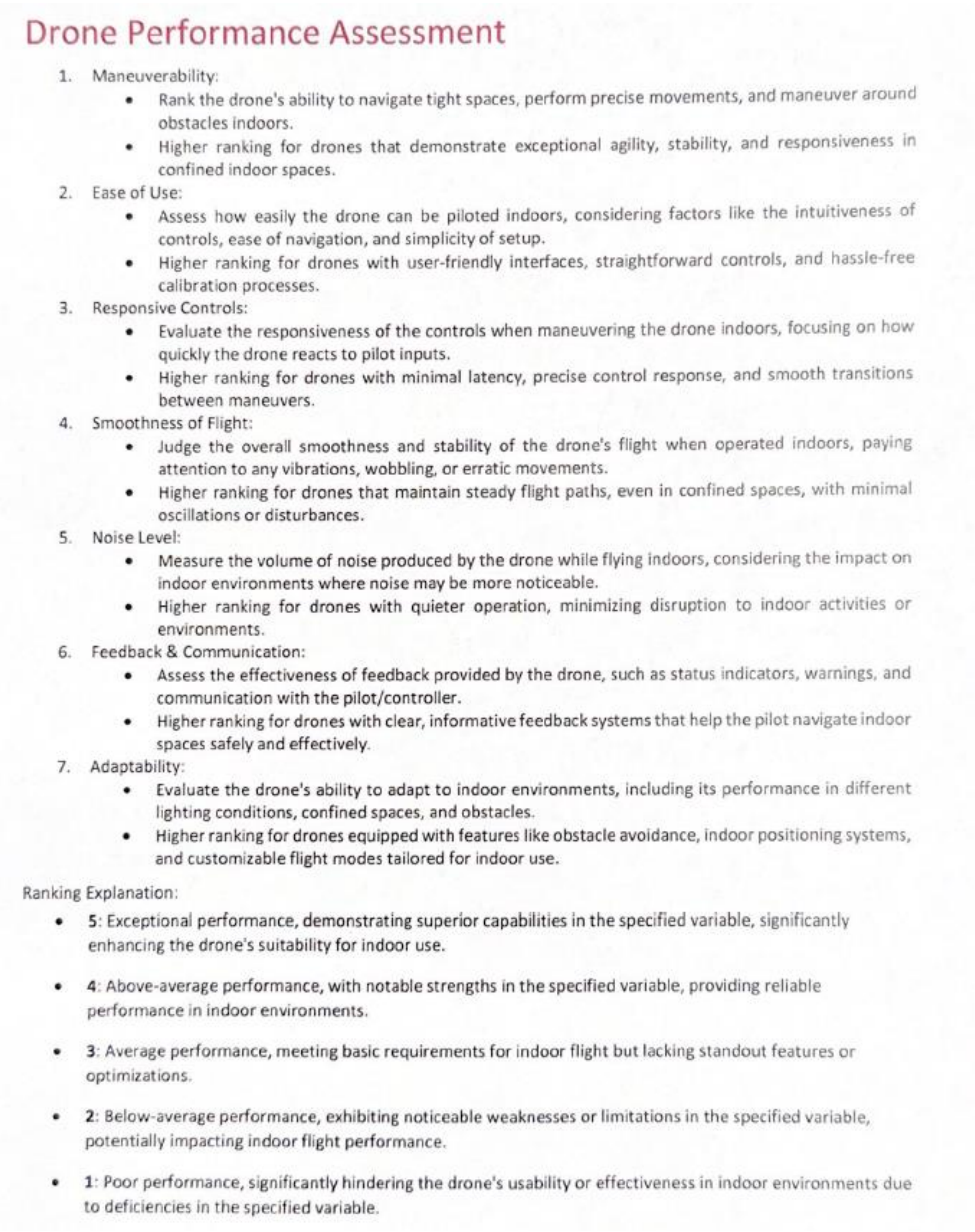
Safety boots	Safety gloves	High visibility	Hard hat	Eye protection	Ear protection	Overall	Other:
No	No	Yes	No	No	Yes	No	

Platforms	Equipment & Accessories
Mavic 3E Tommyknockers Phantom 4 Elios 3	Measuring Tape PVC Pipe Cube Step Ladder + A frame Ladder Saw Horses Tables

Other comment

Flights will be conducted after hours and with spotters monitoring the drone flights to protect against any bystanders.

Figure 28: Indoor Trial Task Sheet



Drone Performance Assessment

1. Maneuverability:
    - Rank the drone's ability to navigate tight spaces, perform precise movements, and maneuver around obstacles indoors.
    - Higher ranking for drones that demonstrate exceptional agility, stability, and responsiveness in confined indoor spaces.
2. Ease of Use:
    - Assess how easily the drone can be piloted indoors, considering factors like the intuitiveness of controls, ease of navigation, and simplicity of setup.
    - Higher ranking for drones with user-friendly interfaces, straightforward controls, and hassle-free calibration processes.
3. Responsive Controls:
    - Evaluate the responsiveness of the controls when maneuvering the drone indoors, focusing on how quickly the drone reacts to pilot inputs.
    - Higher ranking for drones with minimal latency, precise control response, and smooth transitions between maneuvers.
4. Smoothness of Flight:
    - Judge the overall smoothness and stability of the drone's flight when operated indoors, paying attention to any vibrations, wobbling, or erratic movements.
    - Higher ranking for drones that maintain steady flight paths, even in confined spaces, with minimal oscillations or disturbances.
5. Noise Level:
    - Measure the volume of noise produced by the drone while flying indoors, considering the impact on indoor environments where noise may be more noticeable.
    - Higher ranking for drones with quieter operation, minimizing disruption to indoor activities or environments.
6. Feedback & Communication:
    - Assess the effectiveness of feedback provided by the drone, such as status indicators, warnings, and communication with the pilot/controller.
    - Higher ranking for drones with clear, informative feedback systems that help the pilot navigate indoor spaces safely and effectively.
7. Adaptability:
    - Evaluate the drone's ability to adapt to indoor environments, including its performance in different lighting conditions, confined spaces, and obstacles.
    - Higher ranking for drones equipped with features like obstacle avoidance, indoor positioning systems, and customizable flight modes tailored for indoor use.

Ranking Explanation:

- 5: Exceptional performance, demonstrating superior capabilities in the specified variable, significantly enhancing the drone's suitability for indoor use.

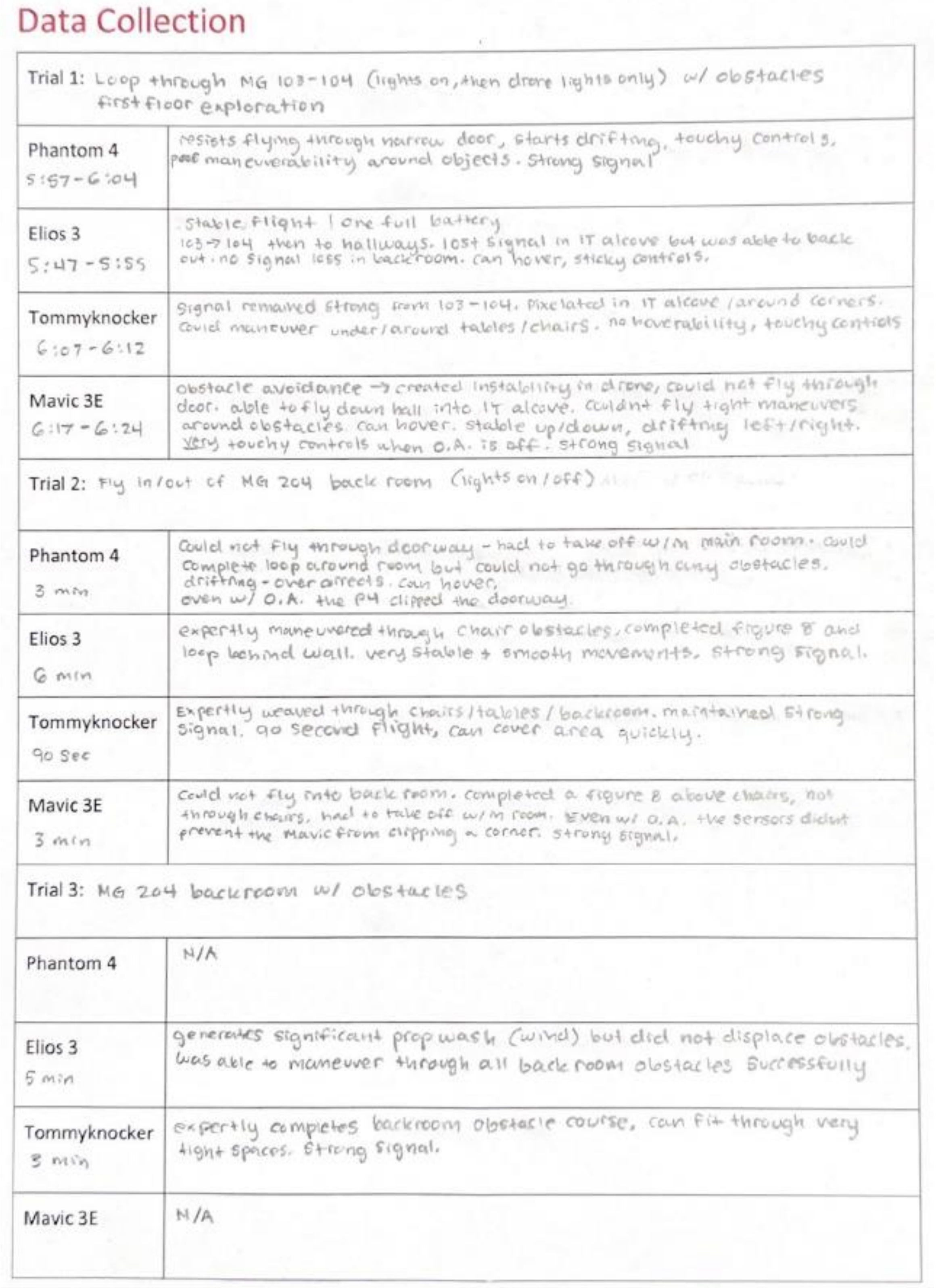
- 4: Above-average performance, with notable strengths in the specified variable, providing reliable performance in indoor environments.

- 3: Average performance, meeting basic requirements for indoor flight but lacking standout features or optimizations.

- 2: Below-average performance, exhibiting noticeable weaknesses or limitations in the specified variable, potentially impacting indoor flight performance.

- 1: Poor performance, significantly hindering the drone's usability or effectiveness in indoor environments due to deficiencies in the specified variable.

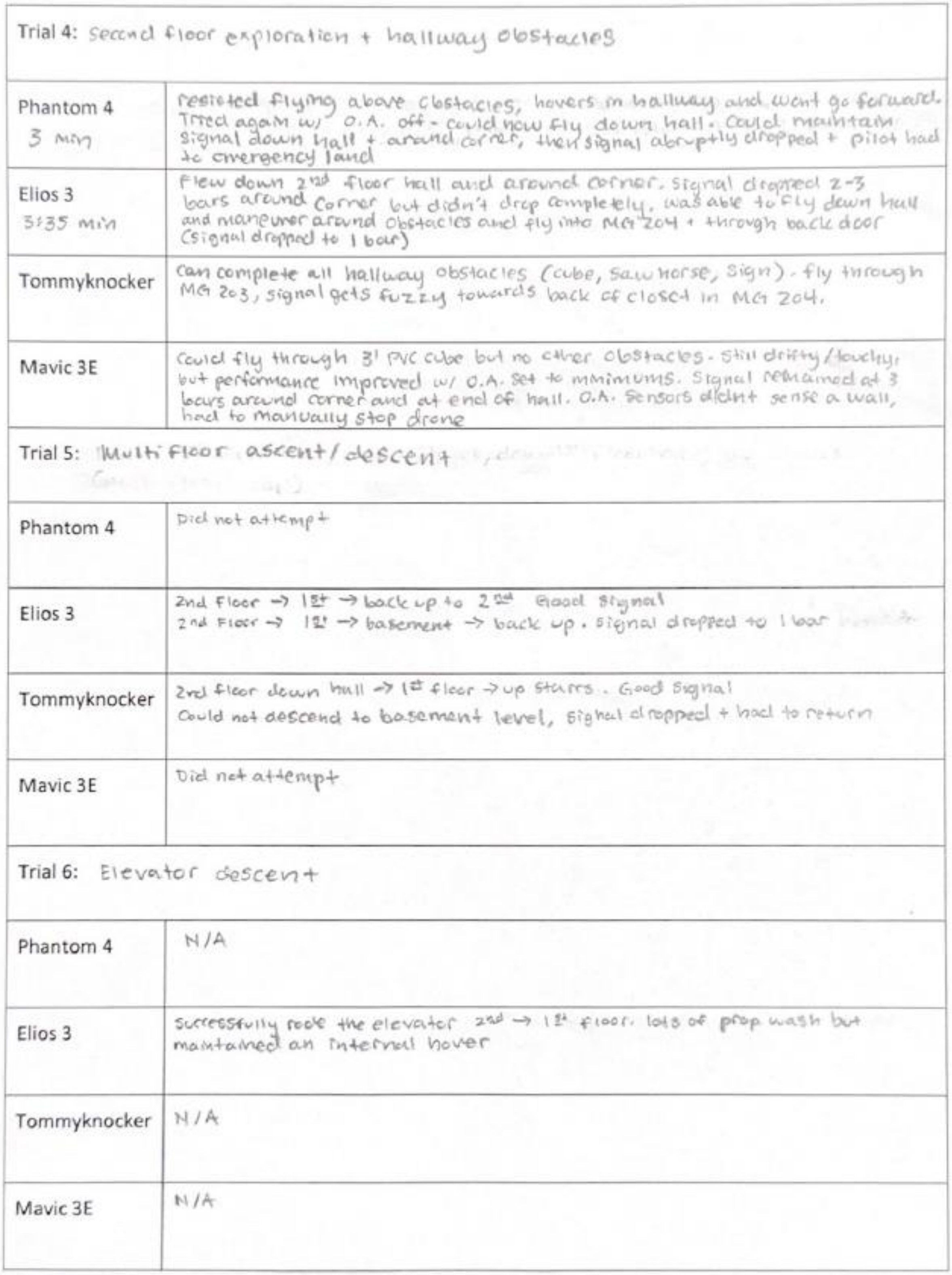
Figure 29: Drone Performance Assessment Criteria



Data Collection

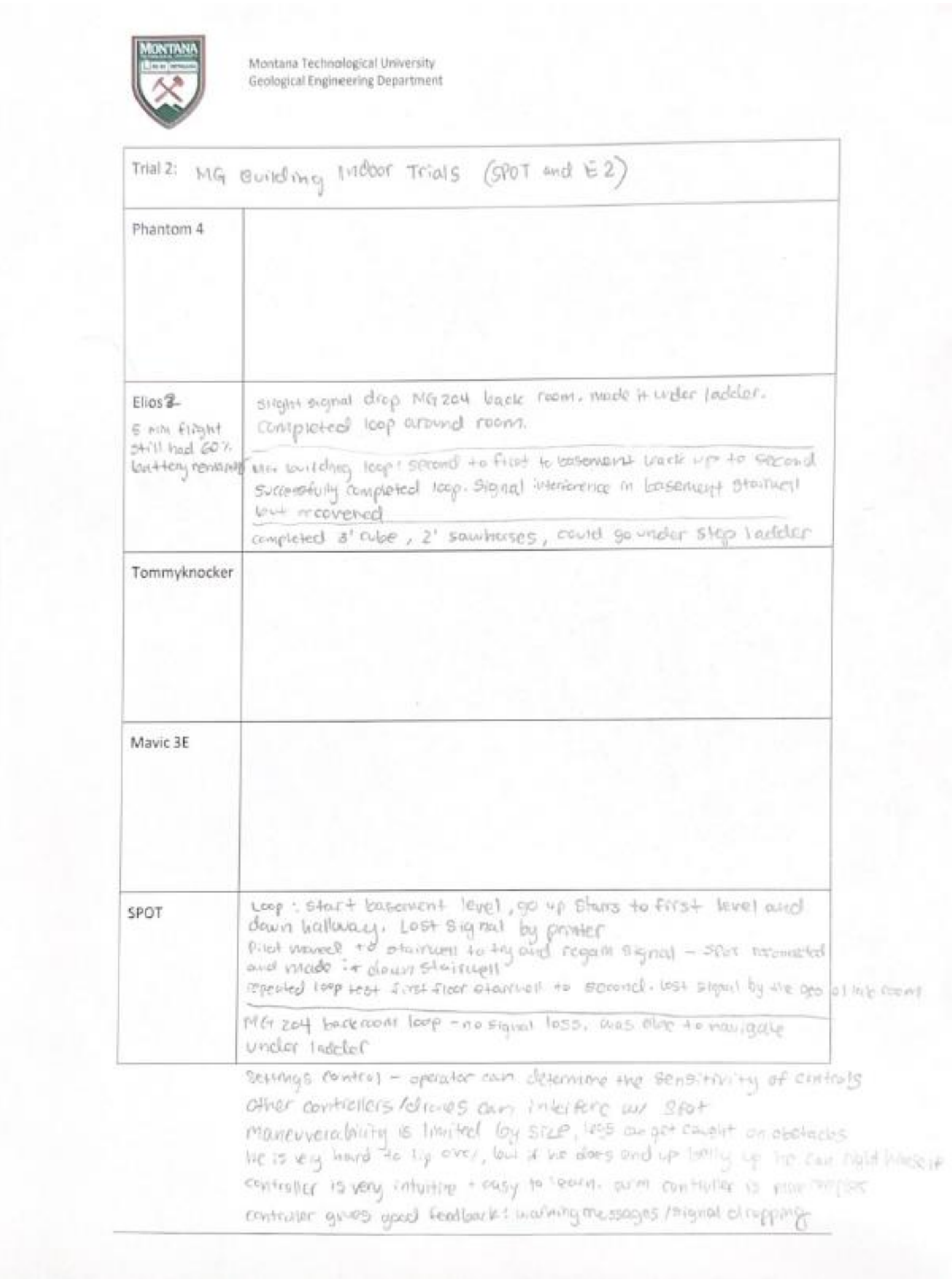
Trial 1: Loop through MG 103-104 (lights on, then drone lights only) w/ obstacles first floor exploration	
Phantom 4 5:57-6:04	resists flying through narrow door, starts drifting, touchy controls, poor maneuverability around objects. Strong signal
Elios 3 5:47-5:55	Stable flight | one full battery 103→104 then to hallways. lost signal in IT alcove but was able to back out. no signal loss in backroom. can hover, sticky controls.
Tommyknocker 6:07-6:12	Signal remained strong from 103-104. Pixelated in IT alcove / around corners. Could maneuver under/around tables / chairs. no hoverability, touchy controls
Mavic 3E 6:17-6:24	obstacle avoidance → created instability in drone, could not fly through door. able to fly down hall into IT alcove. Couldn't fly tight maneuvers around obstacles. can hover. stable up/down, drifting left/right. very touchy controls when O.A. is off. strong signal
Trial 2: Fly in/out of MG 204 back room (lights on / off)	
Phantom 4 3 min	Could not fly through doorway - had to take off w/in main room. could complete loop around room but could not go through any obstacles. drifting - over corrects. can hover. even w/ O.A. the P4 clipped the doorway.
Elios 3 6 min	expertly maneuvered through chair obstacles, completed figure 8 and loop behind wall. very stable + smooth movements. strong signal.
Tommyknocker 90 sec	Expertly weaved through chairs / tables / backroom. maintained strong signal. 90 second flight, can cover area quickly.
Mavic 3E 3 min	Could not fly into back room. completed a figure 8 above chairs, not through chairs. had to take off w/in room. Even w/ O.A. the sensors didn't prevent the Mavic from clipping a corner. strong signal.
Trial 3: MG 204 backroom w/ obstacles	
Phantom 4	N/A
Elios 3 5 min	generates significant prop wash (wind) but did not displace obstacles. was able to maneuver through all back room obstacles successfully
Tommyknocker 3 min	expertly completes backroom obstacle course, can fit through very tight spaces. strong signal.
Mavic 3E	N/A

Figure 30: Indoor Trial Data Collection Sheet 1



Trial 4: Second floor exploration + hallway obstacles	
Phantom 4 3 min	resisted flying above obstacles, hovers in hallway and went go forward. Tried again w/ O.A. off - could now fly down hall. Could maintain signal down hall + around corner, then signal abruptly dropped + pilot had to emergency land
Elios 3 3:35 min	Flew down 2nd floor hall and around corner. Signal dropped 2-3 bars around corner but didn't drop completely. was able to fly down hall and maneuver around obstacles and fly into MG 204 + through back door (signal dropped to 1 bar)
Tommyknocker	can complete all hallway obstacles (cube, saw horse, sign) - fly through MG 203, signal gets fuzzy towards back of closet in MG 204.
Mavic 3E	could fly through 3' PVC cube but no other obstacles - still drifty / touchy, but performance improved w/ O.A. set to minimums. Signal remained at 3 bars around corner and at end of hall. O.A. sensors didn't sense a wall, had to manually stop drone
Trial 5: Multi floor ascent / descent	
Phantom 4	Did not attempt
Elios 3	2nd Floor → 1st → back up to 2nd Good Signal 2nd Floor → 1st → basement → back up. signal dropped to 1 bar
Tommyknocker	2nd floor down hall → 1st floor → up stairs. Good Signal Could not descend to basement level, signal dropped + had to return
Mavic 3E	Did not attempt
Trial 6: Elevator descent	
Phantom 4	N/A
Elios 3	successfully rode the elevator 2nd → 1st floor. lots of prop wash but maintained an internal hover
Tommyknocker	N/A
Mavic 3E	N/A

Figure 31: Indoor Trial Data Collection Sheet 2



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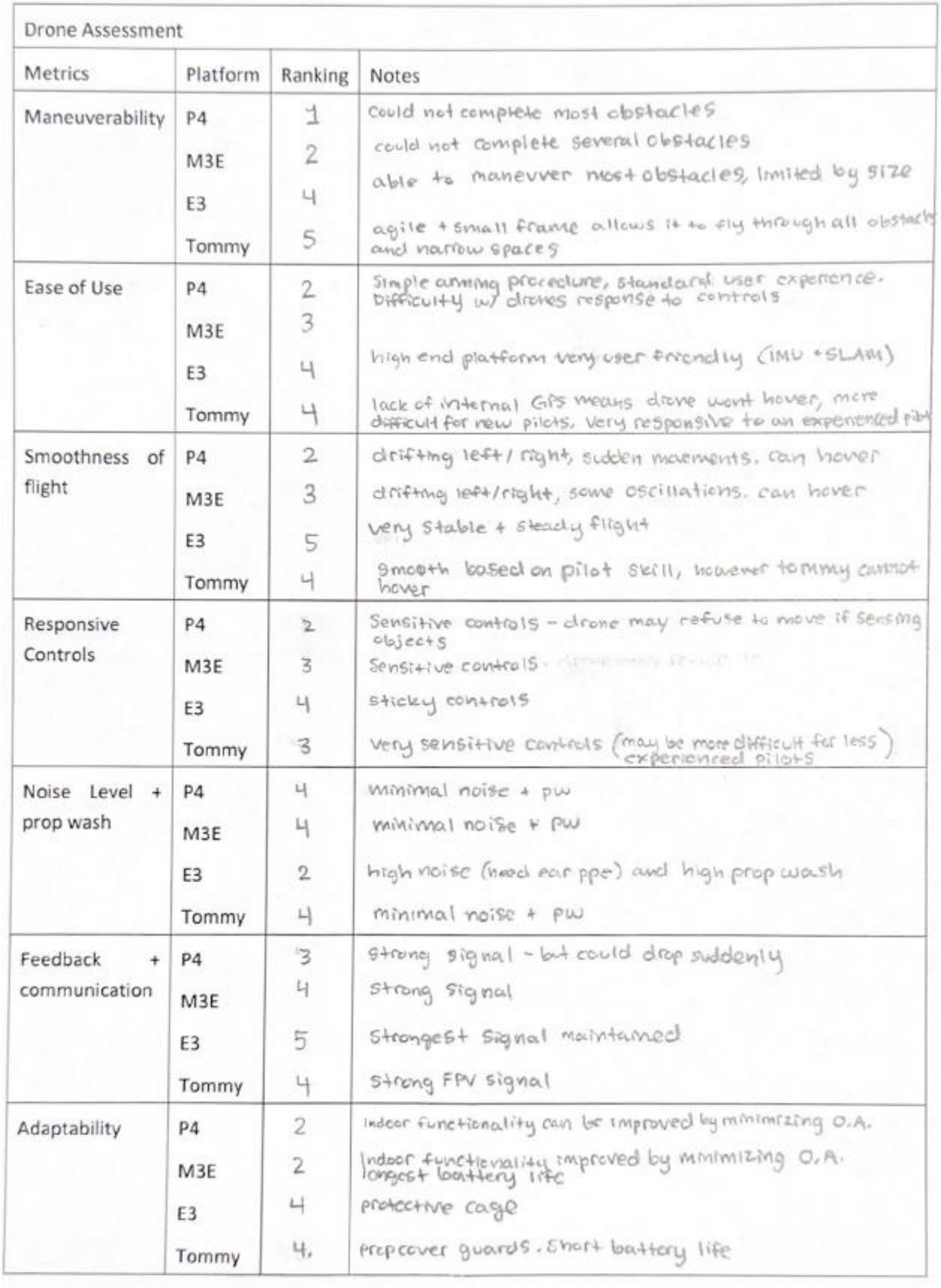
Trial 2: MG Building Indoor Trials (SPOT and E2)	
Phantom 4	
Elios 2 5 min flight still had 60% battery remaining	slight signal drop MG 204 back room. made it under ladder. Completed loop around room. MG building loop: second to first to basement back up to second. Successfully completed loop. Signal interference in basement stairwell but recovered completed 3' cube, 2' sawhorses, could go under step ladder
Tommyknocker	
Mavic 3E	
SPOT	Loop: start basement level, go up stairs to first level and down hallway. Lost signal by printer Pilot moved to stairwell to try and regain signal – Spot reconnected and made it down stairwell repeated loop test first floor stairwell to second. lost signal by the geo lab room MG 204 backroom loop – no signal loss. was able to navigate under ladder

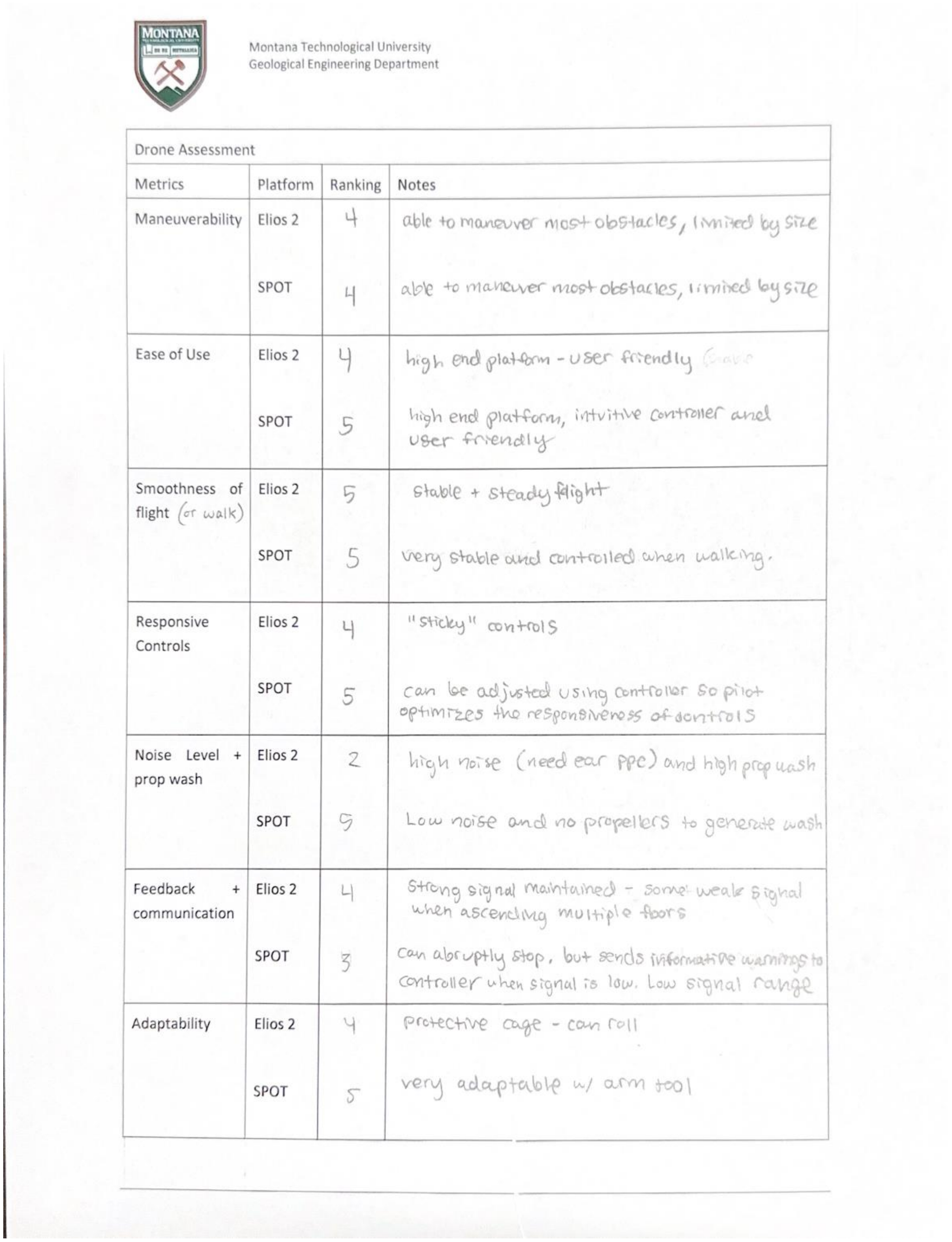
Settings control – operator can determine the sensitivity of controls
Other controllers/drones can interfere w/ Spot
Maneuverability is limited by size, legs can get caught on obstacles
he is very hard to tip over, but if he does end up belly up he can right himself
controller is very intuitive + easy to learn. arm controller is more complex
controller gives good feedback: warning messages/signal dropping

Figure 32: Indoor Trial Data Collection Sheet 3



Drone Assessment			
Metrics	Platform	Ranking	Notes
Maneuverability	P4	1	Could not complete most obstacles
	M3E	2	could not complete several obstacles
	E3	4	able to manevver most obstacles, limited by size
	Tommy	5	agile + small frame allows it to fly through all obstacl and narrow spaces
Ease of Use	P4	2	Simple arming procedure, standard user experience. Difficulty w/ drones response to controls
	M3E	3	
	E3	4	high end platform very user friendly (IMU +SLAM)
	Tommy	4	lack of internal GPS means drone wont hover, more difficult for new pilots. Very responsive to an experienced pil
Smoothness of flight	P4	2	drifting left / right, sudden movements. can hover
	M3E	3	drifting left/right, some oscillations. can hover
	E3	5	very stable + steady flight
	Tommy	4	smooth based on pilot skill, however tommy cannot hover
Responsive Controls	P4	2	Sensitive controls - drone may refuse to move if sensing objects
	M3E	3	Sensitive controls -
	E3	4	sticky controls
	Tommy	3	very sensitive controls (may be more difficult for less experienced pilots)
Noise Level + prop wash	P4	4	minimal noise + pw
	M3E	4	minimal noise + pw
	E3	2	high noise (need ear ppe) and high prop wash
	Tommy	4	minimal noise + pw
Feedback + communication	P4	3	strong signal - but could drop suddenly
	M3E	4	strong signal
	E3	5	Strongest Signal maintained
	Tommy	4	strong FPV signal
Adaptability	P4	2	Indoor functionality can be improved by minimizing O.A.
	M3E	2	Indoor functionality improved by minimizing O.A. longest battery life
	E3	4	protective cage
	Tommy	4.	propcover guards. Short battery life

Figure 33: Indoor Trial Drone Assessment Sheet 1



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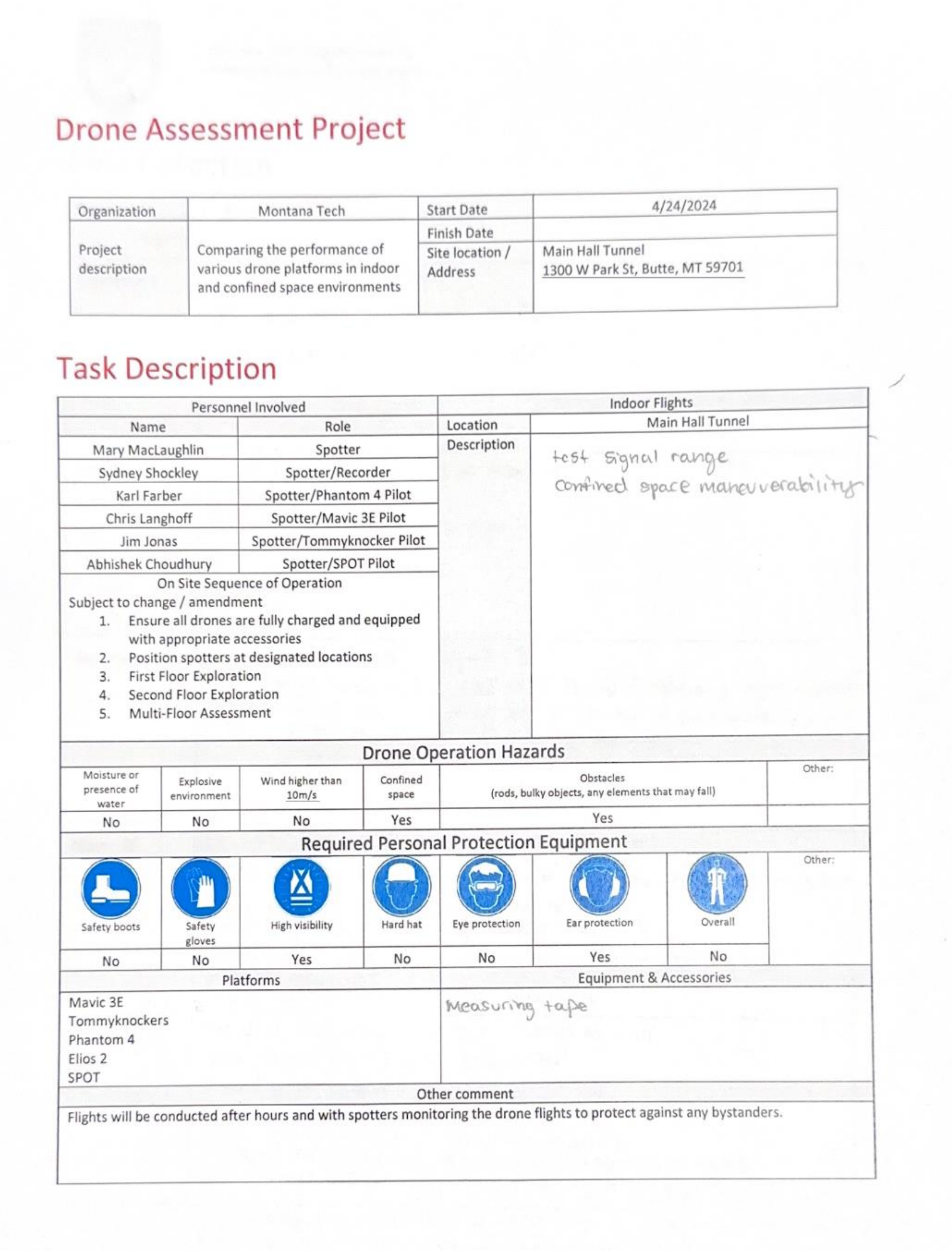
Drone Assessment

Metrics	Platform	Ranking	Notes
Maneuverability	Elios 2	4	able to maneuver most obstacles, limited by size
	SPOT	4	able to manuver most obstacles, limited by size
Ease of Use	Elios 2	4	high end platform - user friendly [illegible]
	SPOT	5	high end platform, intuitive controller and user friendly
Smoothness of flight (or walk)	Elios 2	5	stable + steady flight
	SPOT	5	very stable and controlled when walking.
Responsive Controls	Elios 2	4	"sticky" controls
	SPOT	5	can be adjusted using controller so pilot optimizes the responsiveness of controls
Noise Level + prop wash	Elios 2	2	high noise (need ear PPE) and high prop wash
	SPOT	5	Low noise and no propellers to generate wash
Feedback + communication	Elios 2	4	strong signal maintained - some weak signal when ascending multiple floors
	SPOT	3	can abruptly stop, but sends informative warnings to controller when signal is low. Low signal range
Adaptability	Elios 2	4	protective cage - can roll
	SPOT	5	very adaptable w/ arm tool

Figure 34: Indoor Drone Assessment Sheet 2



Drone Assessment Project

Organization	Montana Tech	Start Date	4/24/2024
Project description	Comparing the performance of various drone platforms in indoor and confined space environments	Finish Date	
		Site location / Address	Main Hall Tunnel 1300 W Park St, Butte, MT 59701

Task Description

Personnel Involved	
Name	Role
Mary MacLaughlin	Spotter
Sydney Shockley	Spotter/Recorder
Karl Farber	Spotter/Phantom 4 Pilot
Chris Langhoff	Spotter/Mavic 3E Pilot
Jim Jonas	Spotter/Tommyknocker Pilot
Abhishek Choudhury	Spotter/SPOT Pilot

Indoor Flights	
Location	Main Hall Tunnel
Description	test signal range confined space maneuverability

On Site Sequence of Operation

Subject to change / amendment

1. Ensure all drones are fully charged and equipped with appropriate accessories
2. Position spotters at designated locations
3. First Floor Exploration
4. Second Floor Exploration
5. Multi-Floor Assessment

Drone Operation Hazards

Moisture or presence of water	Explosive environment	Wind higher than 10m/s	Confined space	Obstacles (rods, bulky objects, any elements that may fall)	Other:
No	No	No	Yes	Yes	

Required Personal Protection Equipment

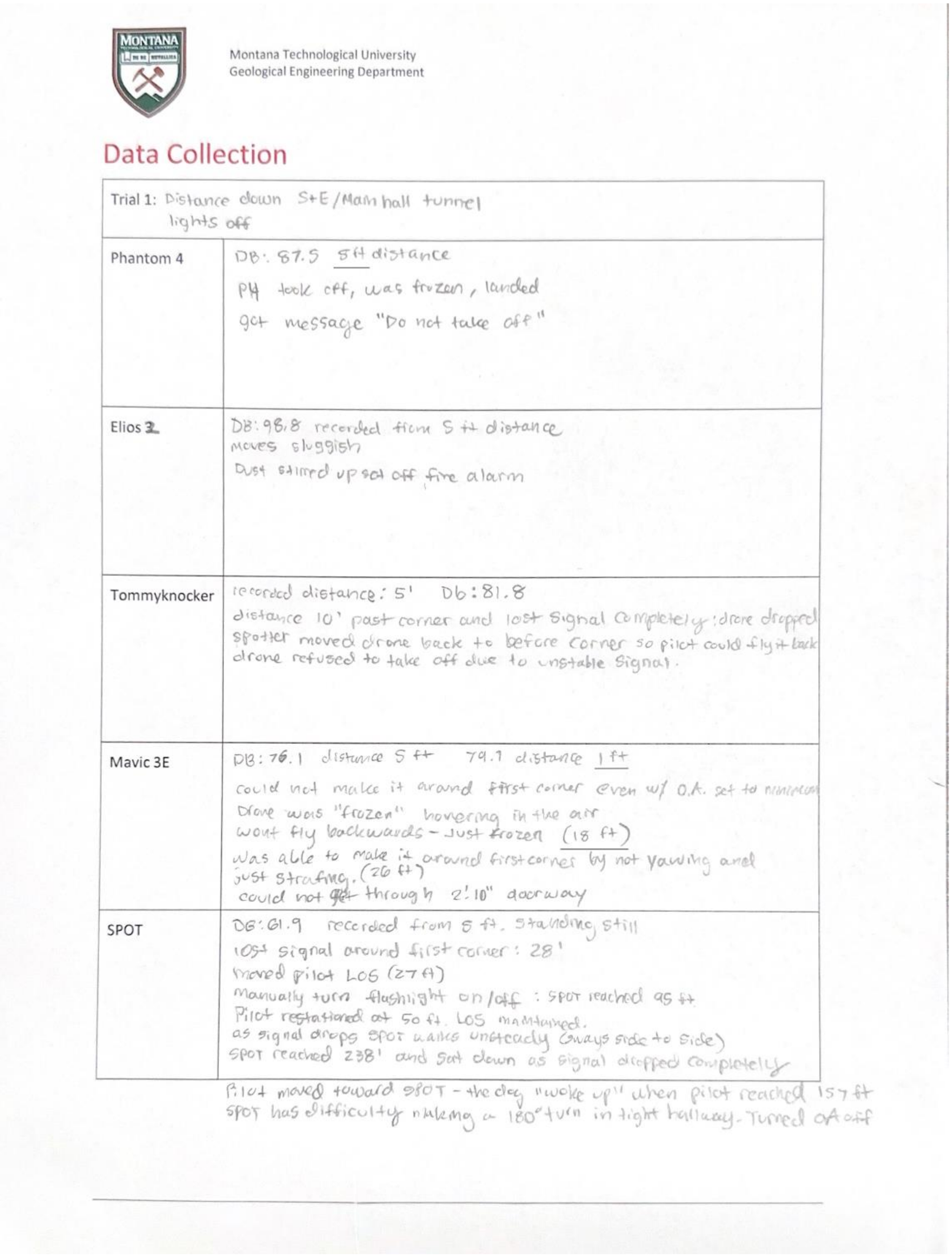
Safety boots	Safety gloves	High visibility	Hard hat	Eye protection	Ear protection	Overall	Other:
No	No	Yes	No	No	Yes	No	

Platforms	Equipment & Accessories
Mavic 3E Tommyknockers Phantom 4 Elios 2 SPOT	Measuring tape

Other comment

Flights will be conducted after hours and with spotters monitoring the drone flights to protect against any bystanders.

Figure 35: Tunnel Trial Task Sheet



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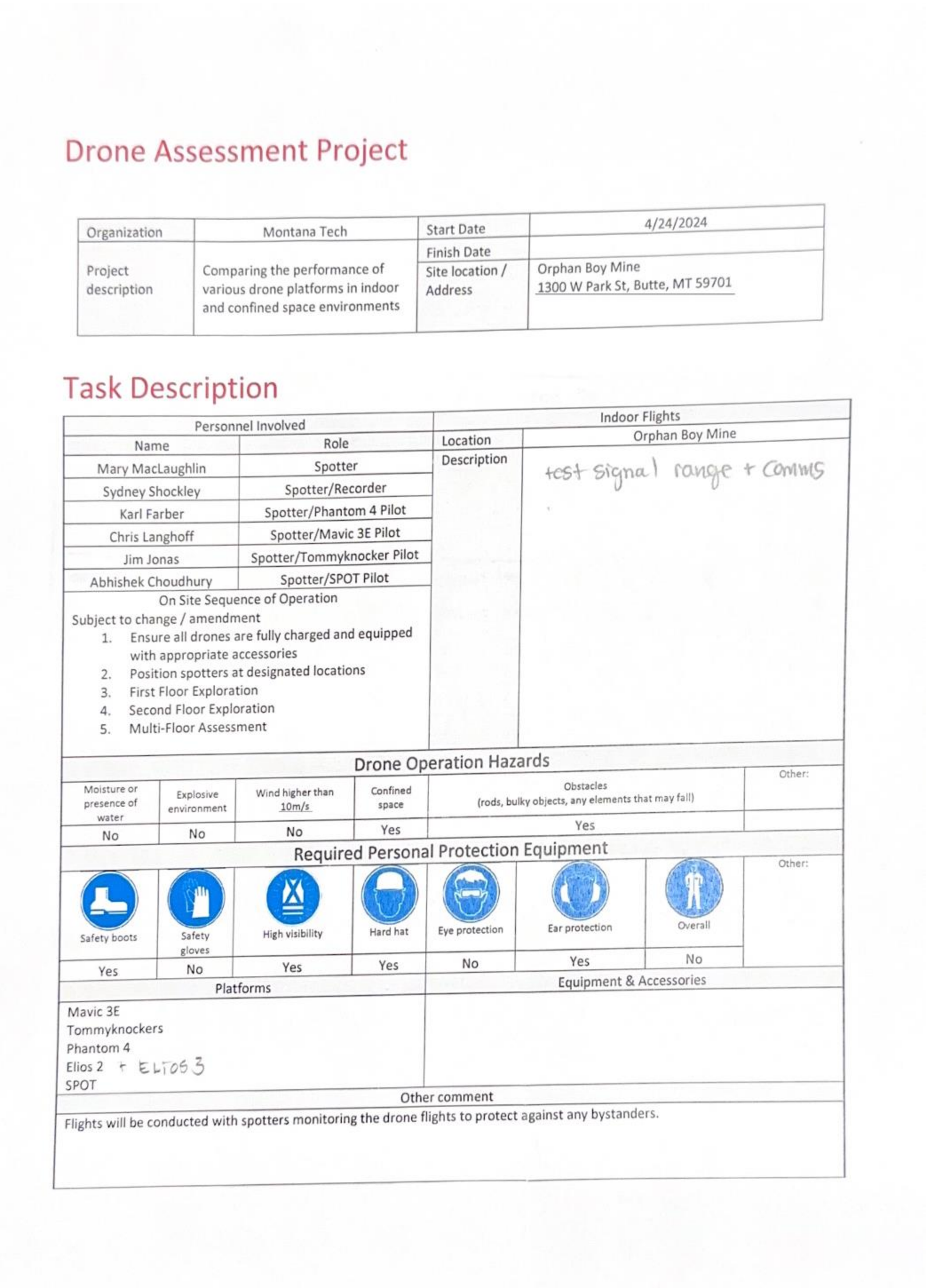
Data Collection

Trial 1: Distance down S+E/Main hall tunnel lights off	
Phantom 4	DB: 87.5 5ft distance P4 took off, was frozen, landed got message "Do not take off"
Elios 2	DB: 98.8 recorded from 5 ft distance moves sluggish Dust stirred up set off fire alarm
Tommyknocker	recorded distance: 5' Db: 81.8 distance 10' past corner and lost signal completely: drone dropped spotter moved drone back to before corner so pilot could fly it back drone refused to take off due to unstable signal.
Mavic 3E	DB: 76.1 distance 5 ft 79.1 distance 1 ft could not make it around ~~first~~ corner even w/ O.A. set to minimum Drone was "frozen" hovering in the air wont fly backwards - Just frozen (18 ft) Was able to make it around first corner by not yawing and just strafing. (26 ft) could not ~~get~~ through 2' 10" doorway
SPOT	DB: 61.9 recorded from 5 ft. standing still lost signal around first corner: 28' moved pilot LOS (27 ft) Manually turn flashlight on/off : SPOT reached 95 ft Pilot restationed at 50 ft. LOS maintained. as signal drops SPOT walks unsteady (sways side to side) SPOT reached 238' and sat down as signal dropped completely

Pilot moved toward SPOT - the dog "woke up" when pilot reached 157 ft
SPOT has difficulty making a 180° turn in tight hallway. Turned ~~OA~~ off

Figure 36: Tunnel Trial Data Collection Sheet



Drone Assessment Project

Organization	Montana Tech	Start Date	4/24/2024
Project description	Comparing the performance of various drone platforms in indoor and confined space environments	Finish Date	
		Site location / Address	Orphan Boy Mine 1300 W Park St, Butte, MT 59701

Task Description

Personnel Involved	
Name	**Role**
Mary MacLaughlin	Spotter
Sydney Shockley	Spotter/Recorder
Karl Farber	Spotter/Phantom 4 Pilot
Chris Langhoff	Spotter/Mavic 3E Pilot
Jim Jonas	Spotter/Tommyknocker Pilot
Abhishek Choudhury	Spotter/SPOT Pilot

Indoor Flights	
Location	Orphan Boy Mine
Description	test signal range + comms

On Site Sequence of Operation

Subject to change / amendment

1. Ensure all drones are fully charged and equipped with appropriate accessories
2. Position spotters at designated locations
3. First Floor Exploration
4. Second Floor Exploration
5. Multi-Floor Assessment

Drone Operation Hazards

Moisture or presence of water	Explosive environment	Wind higher than 10m/s	Confined space	Obstacles (rods, bulky objects, any elements that may fall)	Other:
No	No	No	Yes	Yes	

Required Personal Protection Equipment

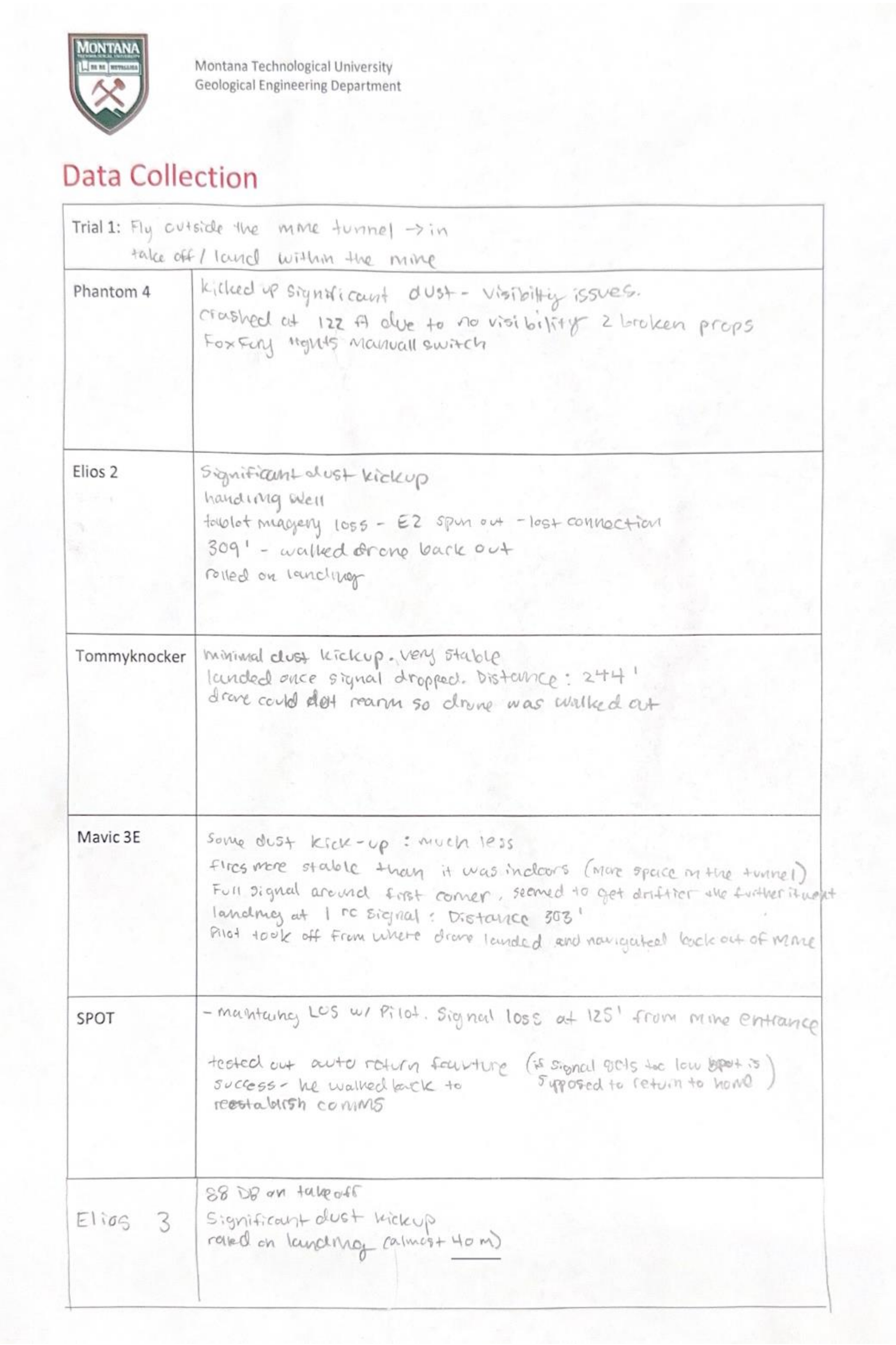
Safety boots	Safety gloves	High visibility	Hard hat	Eye protection	Ear protection	Overall	Other:
Yes	No	Yes	Yes	No	Yes	No	

Platforms	Equipment & Accessories
Mavic 3E Tommyknockers Phantom 4 Elios 2 + ELIOS 3 SPOT	

Other comment

Flights will be conducted with spotters monitoring the drone flights to protect against any bystanders.

Figure 37: Underground Mine Task Sheet



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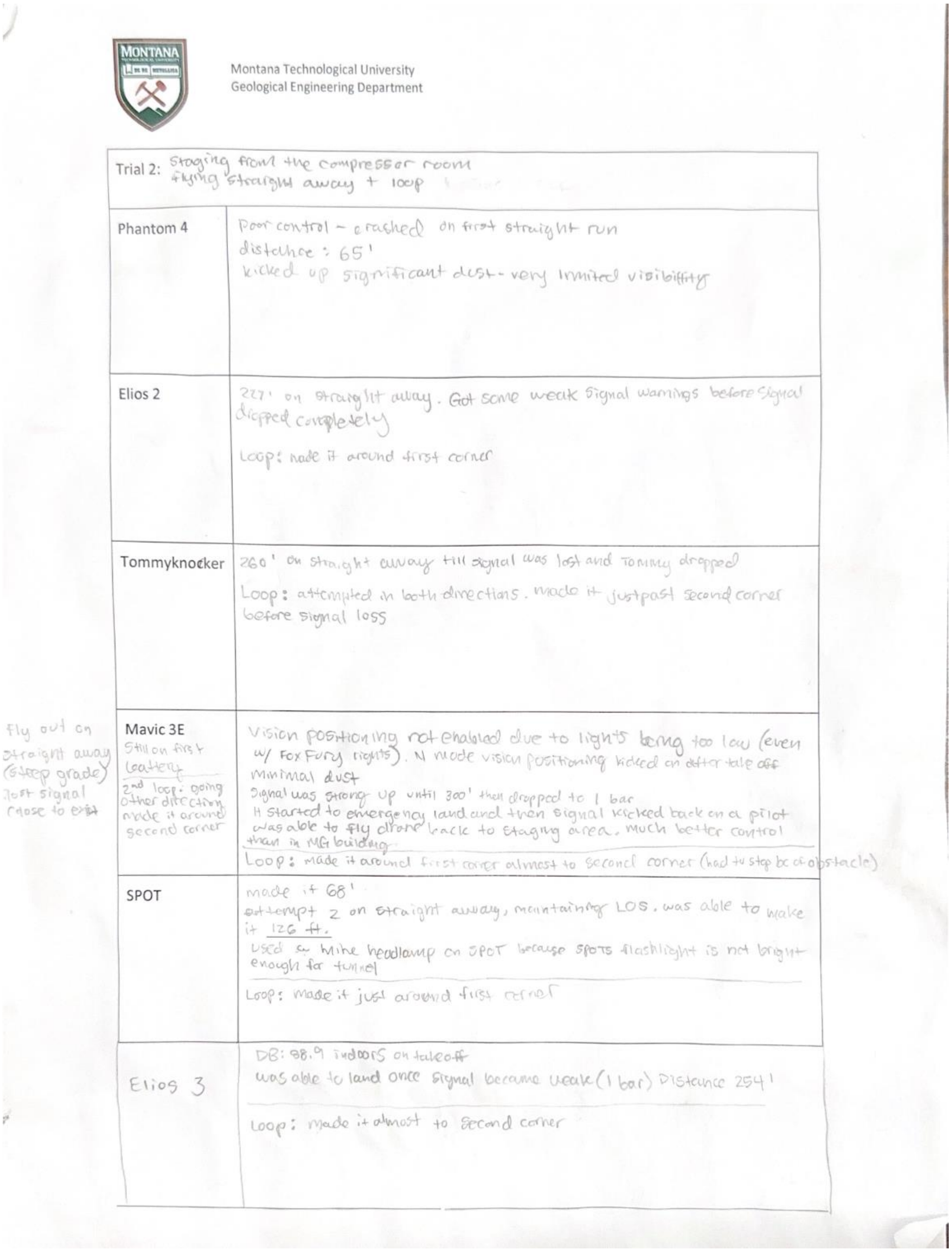
Data Collection

Trial 1: Fly outside the mine tunnel -> in take off / land within the mine	
Phantom 4	kicked up significant dust - visibility issues. crashed at 122 ft due to no visibility 2 broken props FoxFury lights manuall switch
Elios 2	Significant dust kickup handling well tablet imagery loss - E2 spun out - lost connection 309' - walked drone back out rolled on landing
Tommyknocker	minimal dust kickup. very stable landed once signal dropped. Distance: 244' drone could not rearm so drone was walked out
Mavic 3E	Some dust kick-up: much less Flies more stable than it was indoors (more space in the tunnel) Full signal around first corner, seemed to get driftier the further it went landing at 1 rc signal: Distance 303' Pilot took off from where drone landed and navigated back out of mine
SPOT	- maintaining LOS w/ Pilot. Signal loss at 125' from mine entrance tested out auto return feature (if signal gets too low spot is supposed to return to home) success - he walked back to reestablish comms
Elios 3	88 DB on takeoff Significant dust kickup rolled on landing (almost 40 m)

Figure 38: Underground Mine Trial Sheet 1



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Fly out on straight away (steep grade) lost signal close to exit

Trial 2: staging from the compressor room flying straight away + loop	
Phantom 4	Poor control - crashed on first straight run distance : 65' kicked up significant dust - very limited visibility
Elios 2	227' on straight away. Got some weak signal warnings before signal dropped completely Loop: made it around first corner
Tommyknocker	260' on straight away till signal was lost and Tommy dropped Loop: attempted in both directions. made it just past second corner before signal loss
Mavic 3E Still on first battery 2nd loop: going other direction made it around second corner	Vision positioning not enabled due to lights being too low (even w/ FoxFury lights). N mode vision positioning kicked on after take off minimal dust Signal was strong up until 300' then dropped to 1 bar It started to emergency land and then signal kicked back on a pilot was able to fly drone back to staging area. much better control than in MG building Loop: made it around first corner almost to second corner (had to stop bc of obstacle)
SPOT	made it 68' attempt 2 on straight away, maintaining LOS. was able to make it 126 ft. Used ~~a~~ Mine headlamp on SPOT because SPOTs flashlight is not bright enough for tunnel Loop: made it just around first corner
Elios 3	DB: 88.9 indoors on takeoff was able to land once signal became weak (1 bar) Distance 254' Loop: made it almost to second corner

Figure 39: Underground Mine Trial Sheet 2