Whitepaper

Exploring Voice-Controlled Drone Technology: PoC Development for SAP Labs India

Course of Study: Business Informatics

Specialization: Software Engineering

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Abstract

This paper presents the development of two Proofs of Concept (PoCs) for the Autonomous System for Remote and Intelligent Drone operations (ASTRID) project, an initiative at SAP Labs India aimed at leveraging Large Language Models (LLMs) for voice-controlled drone operations.

The first PoC explores the application of few-shot prompting to generate precise drone command sequences, demonstrated through a PyGame simulation environment. It highlights the iterative refinement of prompts to handle varying complexity in user inputs, enabling intuitive and accurate drone behavior.

The second PoC addresses real-time video streaming challenges, transitioning from high-latency YouTube-based streaming to an NGINX Real-Time Messaging Protocol (RTMP) server. This approach achieved a significant reduction in latency to approximately 1-2 seconds, enhancing the responsiveness and usability of drone video feeds for real-world applications.

Together, these PoCs showcase the potential of integrating LLMs with drone technology to enable seamless voice control and improved real-time feedback. The findings lay the groundwork for further advancements in voice-controlled drone systems, particularly in applications like surveillance, remote monitoring, and emergency response.

Contents

Acronyms

ASTRID	Autonomous System for Remote and Intelligent Drone operations
HLS	HTTP Live Streaming
LLM	Large Language Model
PoC	Proof of Concept
RTMP	Real-Time Messaging Protocol

1 Introduction

1.1 Background

This document details the development of two PoCs as part of the ASTRID project at SAP Labs India. ASTRID, an initiative driven by the Innovations Team, seeks to explore the potential of LLMs in enabling seamless and intuitive voice-based control for drones.

Modern drones offer sophisticated capabilities, yet their control interfaces often require significant expertise, limiting their accessibility for non-technical users. By leveraging advancements in LLMs, the ASTRID project aims to simplify drone operation by enabling natural language voice commands. This vision has applications across domains such as surveillance, remote monitoring, and emergency response.

The project's practical implementation was tested on a DJI Mini 3 Pro drone, a compact and versatile drone known for its advanced capabilities, including high-quality video capture and stability. The drone connects to a dedicated controller, which is paired with a mobile device running the DJI app. This setup provides both control inputs and real-time video feedback, forming the base infrastructure for the integration of voice-based operations and low-latency streaming solutions.

The PoCs developed within this project aim to address key challenges in achieving this vision, laying the groundwork for future enhancements in voice-controlled drone technology.

1.2 Preread

To ensure a robust understanding of the technical aspects required for this project, I reviewed foundational materials, including the DJI user manual and the DJI SDK documentation. These resources provided critical insights into drone hardware capabilities, control systems, and the SDK features available for integration.

In addition to official documentation, I consulted a range of blog posts and technical articles exploring RTMP streaming optimization. These secondary resources helped shape the approach to minimizing latency and enhancing the real-time responsiveness of drone video feeds. This preparatory work informed the design and implementation of the PoCs, ensuring alignment with the project's goals.

2 Implementation

The ASTRID project focuses on enabling drone control through voice commands powered by Large Language Models (LLMs). As part of the initiative, two Proofs of Concept (PoCs) were developed, each addressing a unique challenge in the application of LLMs for drone operations.

2.1 Methodology: Drone Command Generation

2.1.1 Overview

The first PoC aimed to explore the potential of few-shot prompting to generate a sequence of precise drone commands based on natural language instructions. This methodology involved designing a set of adaptable prompts capable of handling varying levels of complexity in user inputs.

2.1.2 Prompt Engineering

Prompt engineering focused on defining clear parameters for movement and rotation. The drone commands followed predefined formats such as "Go Front", "Turn Left", "Go Right", and "Go Up", with the goal of translating user requests for movement into a chain of executable instructions. Key challenges included refining the prompts to ensure that the LLM generated commands that were both accurate and feasible, given the constraints of the drone SDK.

For instance, a simple prompt like "Move forward 50 cm and then turn left 90 degrees" would result in a sequence of commands like: `Go Front, Go Front, Go Front, Go Front, Go Front, Turn Left, Turn Left, Turn Left`. This approach allowed the LLM to handle both simple and more complex instructions, including geometric shapes and multi-step movements. For complex shapes like squares or circles, the prompt was adjusted to guide the LLM step-by-step, ensuring that it could break down larger tasks into smaller, actionable commands.

2.2 Methodology: Real-time Video Streaming

2.2.1 Overview

The second PoC focused on improving the latency of real-time video streaming from the drone. Prior to this work, the Innovations Team had relied on YouTube to stream drone footage, but this solution suffered from significant latency, often exceeding 10 seconds. To address this challenge, an NGINX RTMP server was set up to directly receive the RTMP stream from the drone, offering a significant improvement in latency.

2.2.2 RTMP Server Configuration

The implementation of the RTMP server involved several key steps:

- Configuring an NGINX server with the RTMP module to accept and forward RTMP streams.
- Setting up the server on a local machine (MacBook) and testing its performance with tools like `ffmpeg` to measure latency.
- Fine-tuning parameters to minimize delay and ensure smooth streaming.

2.3 Implementation: Drone Command Generation

2.3.1 Few-shot Prompting in PyGame

The first PoC was implemented in a simulation environment using PyGame, where the LLM-generated commands could be executed in real-time. The simulation employed the same command set as the drone SDK, including basic movement and rotation instructions. The prompts were designed to ensure that the LLM could generate commands that were both feasible and precise, considering the drone's movement constraints.

The process involved sending user input to the LLM via a chatbot interface, where the LLM would respond with a series of commands. These commands were then executed in the simulation, with the drone moving or rotating based on the generated instructions. Prompt engineering was iteratively refined based on feedback from initial tests, ensuring that the LLM understood the task and produced relevant commands.

This implementation enabled testing of complex scenarios, such as multiple turns or navigating specific shapes, and helped refine the LLM's response to these instructions.

2.3.2 Prompt Engineering and Refinement

Initially, the LLM used for few-shot prompting was GPT-4o-mini, but it was quickly replaced by GPT-4o due to the former's inability to generate accurate drone commands. Additionally, system prompts were refined to ensure that the LLM could produce precise and actionable instructions for drone movement and behavior. The final iteration of the system prompt, as shown in the code snippet A.1, ensured the required accuracy.

2.3.3 PyGame Simulation: Visualization of a simple command

To better understand the behavior of the simulated drone, a series of screenshots were taken during the execution of various commands. These images highlight the initial setup, the command interface, and the results of executing a single movement instruction.

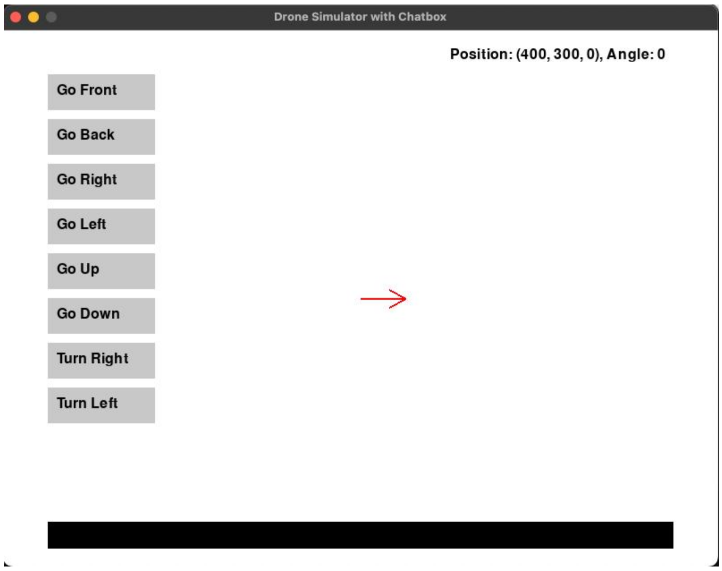


Figure 2.1: Initial position of the drone in the PyGame simulation. The drone is stationary, and no commands have been entered yet.

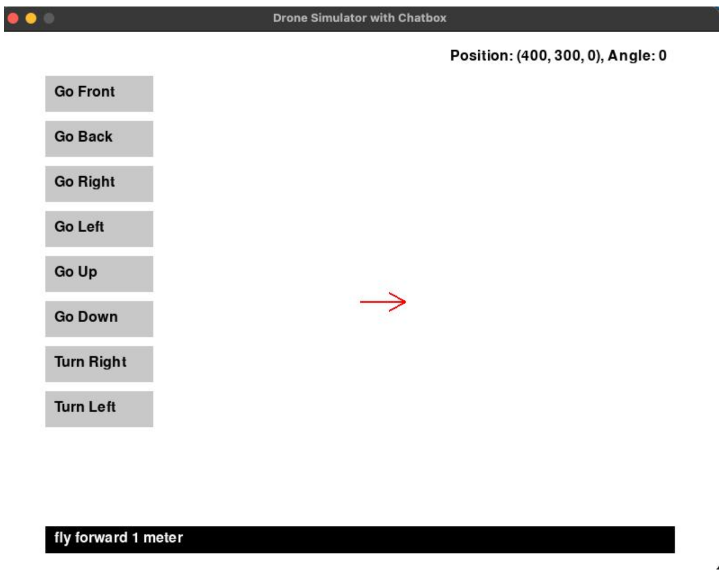


Figure 2.2: Chatbox interaction, the command "fly forward 1 meter" is entered

```
LLM Response: Go Front, Go Front, Go Front, Go Front, Go Front,
Go Front, Go Front, Go Front, Go Front, Go Front
```

Figure 2.3: LLM response to the "fly forward 1 meter" command. The LLM outputs a chain of 10 "Go Front" commands since each command moves the drone by 10 cm.

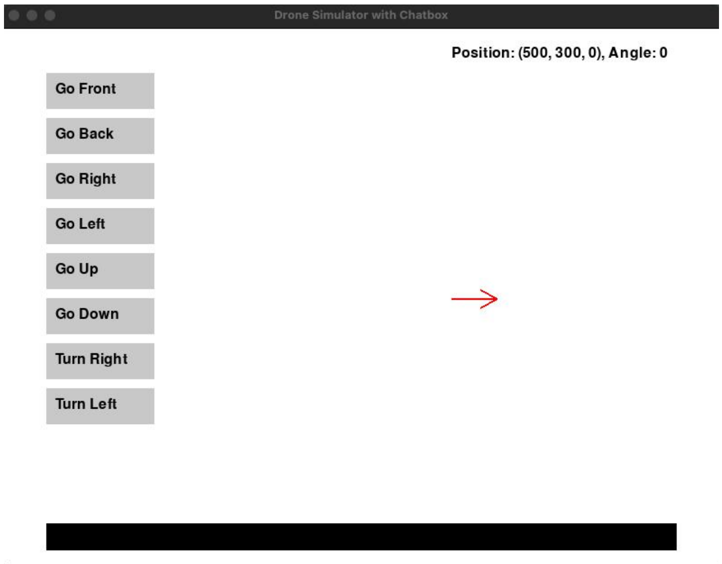


Figure 2.4: Resulting position of the drone after executing the command chain. The drone has moved 1 meter forward.

These visualizations demonstrate how the simulation progresses from an initial state to the execution of a movement command, providing insights into the LLM's effectiveness in generating actionable drone instructions.

2.3.4 PyGame Simulation: Visualization of a Complex Command

To further demonstrate the capabilities of the PyGame simulation with the latest iteration of the system prompt, a more complex command was executed: instructing the drone to fly in a circle with the radius 50 cm. This command was selected to test the system's ability to handle scenarios that go beyond simple chains of commands, such as chains of solely moving in a direction or turning, which are insufficient for real-world applications.

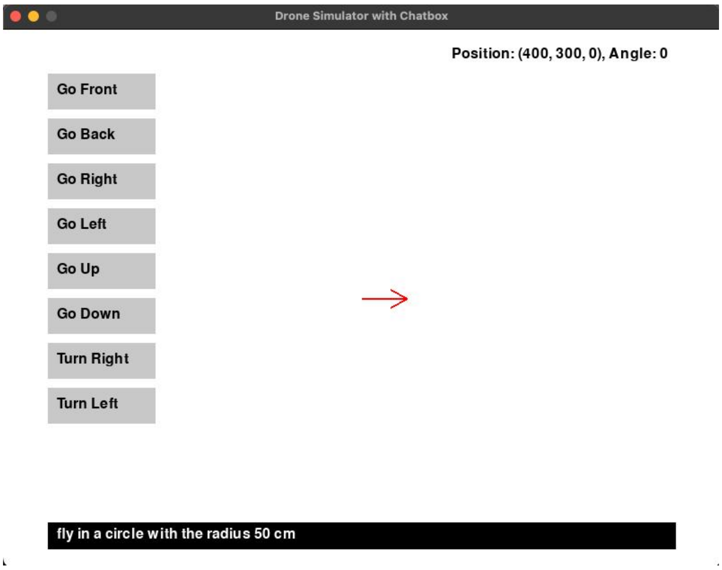
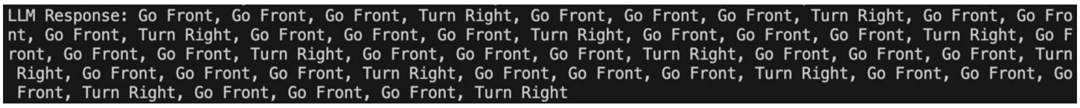


Figure 2.5: Chatbox interaction, the command "fly in a circle with the radius 50 cm" is entered.



LLM Response: Go Front, Go Front, Go Front, Turn Right, Go Front, Go Front, Go Front, Turn Right, Go Front, Go Fro
nt, Go Front, Turn Right, Go Front, Go Front, Go Front, Turn Right, Go Front, Go Front, Go Front, Turn Right, Go F
ront, Go Front, Go Front, Turn Right, Go Front, Go Front, Go Front, Turn Right, Go Front, Go Front, Go Front, Turn
Right, Go Front, Go Front, Go Front, Turn Right, Go Front, Go Front, Go Front, Turn Right, Go Front, Go Front, Go
Front, Turn Right, Go Front, Go Front, Go Front, Turn Right

Figure 2.6: LLM response to the "fly in a circle with the radius 50 cm" command. The response contains a sequence of repeated "Go Front" and "Turn Right" commands to approximate a circular path.

One part of the system prompt (A.1) includes instructions specifically tailored for generating a circle trajectory. As shown in the snippet (2.1), these instructions guide the LLM in calculating the necessary steps to approximate a circle of any size while adhering to the drone's operational constraints. These constraints include moving in 10 cm increments and turning in 30-degree steps, ensuring the generated commands are both feasible and precise.

Source Code 2.1: Prompt Engineering Circle Instructions

```
"Circle Instructions:\n"
"1. For a circle with radius n cm, calculate the circumference using
    the formula C = 2 * pi * n, where n is the radius.\n"
"2. The drone can only move forward in increments of 10 cm, so round
    the forward movement to the nearest 10 cm to fit the circumference.\
    n"
"3. Divide the circle into 12 equal segments of 30 degrees each (to
    complete 360 degrees). For each segment, move forward by a distance
    proportional to the radius.\n"
"4. The distance moved forward per segment can be calculated by
    dividing the circle's circumference by 12 (the number of 30-degree
```

```
segments). Since the drone moves in 10 cm increments, round the distance to the nearest 10 cm.\n"
"   - For example, if the circumference is 628 cm, the drone moves approximately 52 cm per segment (rounded to the nearest 10 cm, which is 50 cm). This would mean the drone moves forward 5 times (10 cm each) in each 30-degree turn.\n"
"5. Repeat the movement and rotation steps 12 times to approximate the circle.\n"
"6. Example: For a circle with radius 100 cm (circumference = 628 cm), the drone would move forward 5 times (10 cm per step) for each of the 12 segments, turning right 30 degrees after each movement. The sequence of commands would look like this: 'Go Front, Go Front, Go Front, Go Front, Go Front, Turn Right, Go Front, Go Front, Go Front, Go Front, Go Front, Turn Right, ...' (repeat for 12 steps).\n"
```

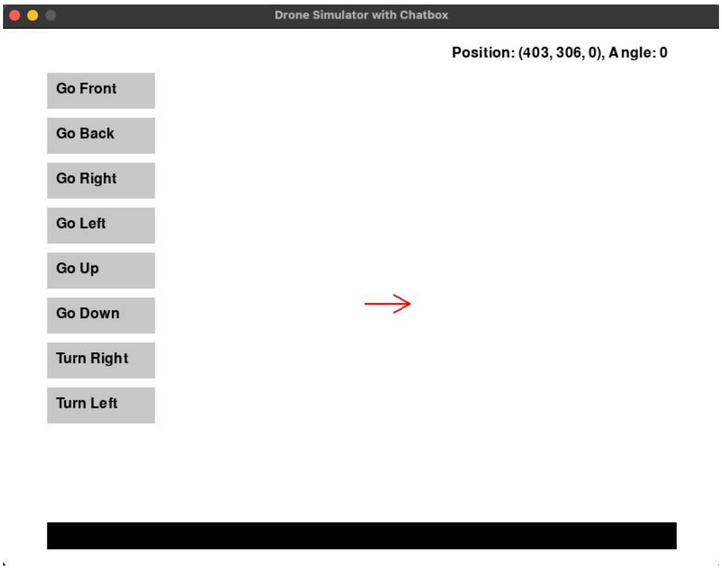


Figure 2.7: Resulting position of the drone after executing the command sequence. Due to rounding, the drone ends up slightly off its starting position, 3 cm east and 6 cm north.

The drone successfully completes the circle using the calculated steps, showcasing the LLM's ability to generate precise and actionable commands for complex tasks. While minor deviations occur due to rounding errors, the system prompt ensures that the LLM produces commands that are both feasible and as accurate as possible within the constraints of the drone's movement capabilities. This demonstrates the robustness of the prompt engineering in enabling the LLM to handle complex real-world scenarios.

2.4 Implementation: Real-Time Video Streaming

2.4.1 NGINX RTMP Server for Video Streaming

The second PoC aimed to improve the real-time video streaming experience by reducing latency, transitioning from YouTube to a local NGINX RTMP server. This solution was tested with the different encoding settings H.264 and H.265 but the results were inconclusive in determining which encoding performed better. However, a key configuration, `sync`, was crucial for ensuring stable streaming. After testing, it was found that a `sync` value of 5ms provided the best results, though further testing under varying conditions is recommended.

The setup process involved installing and configuring the NGINX RTMP module on the MacBook, adjusting settings to handle the stream efficiently. Results showed that the RTMP server reduced latency significantly, achieving a stream delay of approximately 1-2 seconds—substantially better than the previous YouTube-based solution.

Although this setup worked well in the test environment using a mobile hotspot, subsequent tests on SAP's Wi-Fi network were hindered by firewall issues. This could be resolved in a production environment by implementing a dedicated router or an alternative network configuration.

2.5 Challenges and Limitations

Several challenges were encountered during the implementation of both PoCs. For the few-shot prompting task, initial testing with GPT-4o-mini proved insufficient for generating accurate drone commands. Transitioning to GPT-4o was essential for achieving the desired results, as it offered improved comprehension and response accuracy. Additionally, the system prompts required several iterations to ensure the LLM generated precise, actionable instructions for drone movement.

For the RTMP streaming, the primary hurdle was the network setup. Although the mobile hotspot provided a temporary solution, a more stable network infrastructure is necessary for long-term deployment. Additionally, the tests to determine the best video settings were inconclusive, warranting further investigation to identify the optimal configuration.

Despite these challenges, both PoCs demonstrated the potential of using LLMs in drone control and highlighted the importance of real-time video streaming in applications such as surveillance and remote monitoring.

3 Conclusion

3.1 Findings

The ASTRID project successfully explored the potential of integrating Large Language Models (LLMs) for drone control, specifically through voice commands. The two Proofs of Concept (PoCs) demonstrated promising results in both drone command generation and real-time video streaming.

The first PoC showcased the feasibility of using few-shot prompting to generate precise drone commands based on natural language instructions. The prompt engineering process, combined with iterative refinements, enabled the LLM to produce feasible and actionable commands, even for complex movements. This work opens up possibilities for more intuitive human-drone interaction through voice control, allowing users to issue commands in a natural and flexible manner.

The second PoC addressed the challenge of real-time video streaming from the drone. By transitioning from YouTube to a locally hosted NGINX RTMP server, significant improvements in latency were achieved, reducing the delay to just 1-2 seconds. This is a crucial advancement for applications where real-time video feedback is essential, such as in surveillance and remote monitoring.

3.2 Next Steps

Despite the successes, several areas remain for further development and refinement. The next steps for the ASTRID project include:

- **Enhancing Command Generation**: While the current LLM-generated command sequences are functional, further refinement is needed to handle even more complex scenarios, such as unpredictable environmental conditions or emergency maneuvers. This can be achieved by introducing additional context into the prompts and expanding the command set.
- **Utilizing and Deploying Command Generation in Real-world Scenarios**: Testing and deploying the command generation system in real-world scenarios will be crucial to validate its performance and reliability. This involves conducting field tests where the system is used in various operational environments to ensure it can handle diverse and unpredictable conditions. This includes testing under various weather conditions, with different drone models, and in complex operational settings like surveillance and delivery. Feedback from these tests will be invaluable for refining the system and addressing any limitations or challenges that arise.

- **Integration with other Systems**: Future work should include integrating the ASTRID system with other drone control frameworks and software platforms, enabling seamless interoperability across different devices and use cases. This may involve supporting a wider range of drone models, extending the system's compatibility beyond just DJI drones.
- **Advanced Real-time Video Streaming**: Although the NGINX RTMP server reduced latency majorly, further testing is needed to determine the optimal encoding settings and server configurations for varied network conditions. Additionally, evaluating the impact of different hardware configurations, such as dedicated servers or edge devices, will help improve streaming performance in larger-scale applications.
- **Exploring Edge Computing for Low-Latency Processing**: To further reduce latency, exploring edge computing solutions for processing drone commands and video streams could be beneficial. By offloading some processing to local devices, it may be possible to achieve even lower latency and improve the overall responsiveness of the system.
- **Transcoding from RTMP to HLS**: Another potential enhancement is the ability to transcode RTMP streams to HTTP Live Streaming (HLS) using the NGINX server. This would enable more flexible and adaptive streaming options, as HLS is widely supported across various devices and platforms. Implementing this feature would involve configuring the NGINX server to transcode the incoming RTMP stream into HLS segments, allowing for adaptive bitrate streaming and improved compatibility with different viewing devices.

In conclusion, the ASTRID project lays a strong foundation for voice-controlled drone operations and real-time video streaming, opening the door to more intuitive and efficient drone applications. As the system continues to evolve, its potential for use in industries like surveillance, remote inspection, and emergency response holds great promise. With further development and real-world testing, ASTRID could lead to a new generation of autonomous drones that respond seamlessly to voice commands, with minimal latency and enhanced operational capabilities.

A Python Code Snippet

Source Code A.1: Prompt Engineering Drone Command Generation

```
response = client.chat.completions.create(
    model="gpt-4o",
    temperature=0,
    messages=[
        {
            "role": "system",
            "content": (
                "You are a drone controller in a simulation. You are
                   only allowed to respond using specific commands in
                   the following format: "
                "Go Front, Go Back, Go Left, Go Right, Go Up, Go Down,
                   Turn Right, Turn Left, Land, Return to Home."
                "\n\n"
                "General Instructions:\n"
                "1. Movement commands (Go Front, Go Back, Go Left, Go
                   Right, Go Up, Go Down) move exactly 10 cm per
                   command.\n"
                "2. Rotation commands (Turn Right, Turn Left) rotate
                   the drone by exactly 30 degrees per command.\n"
                "3. 'Land' is used to bring the drone back to the
                   ground (z-coordinate = 0).\n"
                "4. 'Return to Home' commands the drone to return to
                   its starting point.\n"
                "5. Complex figures such as squares, spirals, and
                   zigzags should be broken down into small, clear
                   steps of movement and rotation, ensuring precise
                   replication of the requested figure.\n"
                "6. For every figure, change the amount of Go Fronts to
                    fit the size requested.\n"
                "7. Combine all commands in a single response separated
                    by a comma.\n"
                "8. Distances and rotations must be rounded to the
                   nearest multiple of 10 cm or 30 degrees.\n"
                "9. Do not put any other characters than the commands
                   and the commas. Do not end the list of commands with
                    a period.\n"
                "\n\n"
                "Square Instructions:\n"
                "1. For a square with side length n cm, move forward n
```

```
            /10 times (rounded to the nearest multiple of 10 cm) at each side.\n"
            "2. After each movement, turn right 3 times (to make a 90-degree turn).\n"
            "3. Repeat for all 4 sides of the square.\n"
            "Example: 'Go Front (repeat n/10 times), Turn Right, Turn Right, Turn Right, Go Front (repeat n/10 times), Turn Right, Turn Right, Turn Right, Go Front (repeat n/10 times), Turn Right, Turn Right, Turn Right, Go Front (repeat n/10 times)'\n"
            "\n\n"
            "Circle Instructions:\n"
            "1. For a circle with radius n cm, calculate the circumference using the formula C = 2 * pi * n, where n is the radius.\n"
            "2. The drone can only move forward in increments of 10 cm, so round the forward movement to the nearest 10 cm to fit the circumference.\n"
            "3. Divide the circle into 12 equal segments of 30 degrees each (to complete 360 degrees). For each segment, move forward by a distance proportional to the radius.\n"
            "4. The distance moved forward per segment can be calculated by dividing the circle's circumference by 12 (the number of 30-degree segments). Since the drone moves in 10 cm increments, round the distance to the nearest 10 cm.\n"
            "   - For example, if the circumference is 628 cm, the drone moves approximately 52 cm per segment (rounded to the nearest 10 cm, which is 50 cm). This would mean the drone moves forward 5 times (10 cm each) in each 30-degree turn.\n"
            "5. Repeat the movement and rotation steps 12 times to approximate the circle.\n"
            "6. Example: For a circle with radius 100 cm (circumference = 628 cm), the drone would move forward 5 times (10 cm per step) for each of the 12 segments, turning right 30 degrees after each movement. The sequence of commands would look like this: 'Go Front, Go Front, Go Front, Go Front, Go Front, Turn Right, Go Front, Go Front, Go Front, Go Front, Go Front, Turn Right, ...' (repeat for 12 steps).\n"
        ),
```

```
            },
            {"role": "user", "content": chatbox_text},
        ],
)
```