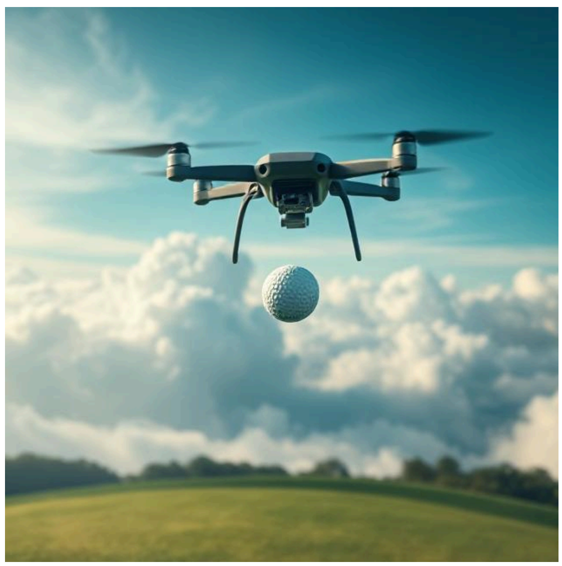
ROB498: Robotics Capstone Design
Team Design Proposal

PARSIGHT



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Project Overview

Golf is a sport that demands physical strength, accuracy, and experience reading the greens, but it also heavily relies on the player having good vision [1]. Skills such as depth perception, hand-eye coordination, reaction time, contrast sensitivity, and fixation are essential for judging distances, aligning shots, and tracking the ball as it soars fast and far [2].

This sport has become an increasingly popular pastime among seniors, with participation among those aged 65 and older rising by 64% in the past decade and those 50+ making up 43% of U.S. golfers in 2024. Golf is an ideal sport for this demographic with physical, mental, and social benefits. However, as golfers age, many report increasing challenges in tracking and locating the ball after hitting a shot [3]. One golfer shared, "I could always follow a golf ball... Now? [...] following a drive? Not a scooby!" [4]. Another says, "It practically disappears once it reaches near its apex. Sometimes I can't even track it that far." [5]. These experiences highlight how age-related vision decline adds strain to an already challenging sport.

Tracking the ball is a central part of golf with no existing commercial solutions that aim to reduce the strain of ball-searching for senior golfers. By addressing this challenge, we hope to enhance their enjoyment and help them focus more on the game itself. Thus, our problem statement is as follows: Design a drone that tracks and follows the trajectory of live golf balls in real time, providing the elderly with an assistive visual marker. The proposed drone solution will involve using a camera and computer vision to keep a flying golf ball within its camera's field of view.

Success will be determined by the drone's ability to consistently track and follow a golf ball in real time. Key metrics that will be measured are the percentage of time the ball remains in the field of view of the drone, the drone's movement reaction time, its collision avoidance with the ball and other obstacles, and the final position of the drone relative to the golf ball's resting location.

Background

As a group, we share a passion for athletics and value altruism, autonomy, and creativity, believing that drones could bring unique and exciting functionality enhancements to the world of sports. Our problem statement reflects our value of altruism by focusing on a solution that improves seniors' ability to enjoy golf and promotes inclusivity in the sport. Our proposed design space also aims to give autonomy to golfers by acting solely as a visual aid, allowing players to independently track their shots without altering the traditional golfing experience. This project scope satisfies our team's value of creativity, as the solution space is novel and exciting, and will require us to utilize both past course knowledge and learn new skills.

There are existing designs that address the opportunity of golf ball tracking. We will evaluate whether they could meet the specific needs of senior golfers and our problem statement.

Augmented Reality (AR) Golf Shot Tracer: Displaying golf ball trajectory using AR has been realized in solutions like *TopTracer* and *Shot Tracer*, which are used by ~28,000 PGA professionals worldwide, officially used by the Professional Golfers' Association (PGA) of America [6], and accessible to regular golfers through mobile apps [7]. The PGA tour has also combined AR with drones to provide shot tracking from an aerial perspective [8]. These existing designs primarily enhance the experience for spectators by displaying the golf ball's trajectory on TV or social media. They are not designed for real-time tracking for the golfer and some even allow users to adjust the trajectory if it doesn't "appear" to their liking [9]. As a result, these solutions do not address our problem statement to provide real-time visual tracking assistance for senior golfers.

Manually Piloted Drones: Another existing solution for real-time golf ball tracking involves a dedicated pilot manually flying a drone to track shots [10] [11]. Similarly to AR Golf Shot Trackers, this primarily benefits viewers with dynamic camera angles. Having a dedicated pilot also drastically affects the original golfing experience, contradicting our value of autonomy.

Follow-Me Drones: Many commercial drones are equipped with the ability to autonomously track a subject and have been used for various sports applications such as skateboarding or biking [12]. These general solutions do not consider following small objects travelling in the air at high speeds, such as a golf ball, and thus, also do not target our problem statement.

By considering the limitations of existing solutions, it is evident there is a gap in the market for a drone that autonomously tracks a golf ball in real-time and helps senior golfers locate their shots.

Design Objectives

The overall goal of this project is to develop a drone solution that assists senior golfers by tracking golf balls after long tee-offs, providing a visual marker for the ball's location. Given limited time and resources, the project has been scoped to address the identified stakeholder needs in an impactful manner while maintaining feasibility by leveraging our skills in segmentation, tracking, computer vision, and control systems. Ideas such as 3D ball trajectory reconstruction using Gaussian Splatting, and ball retrieval by the drone were excluded from our scope as these features, while valuable, are not critical to achieving the overall goal. The requirements model, shown in *Table 1*, outlines the key objectives, functions, and constraints of our design space.

Objectives (BE/HAVE)	Functions (DO)	Constraints (SATISFY)
• **Serve as Visual Output:** Provide a visible marker over the ball such that the location is visible from a distance. • **Accessibility:** Solution is simple and intuitive, and minimises interaction and complexity. • **Safe Fly:** Predictable and controlled flights. • **Small/Lightweight:** Easy to transport, compact. • **Durable Design**: Able to handle minor impacts without loss of function.	• **Capturing Environment:** Use a camera (e.g. RGB-D, RealSense, etc.) to obtain visual information about the environment. • **Segmentation:** Accurately detect golf ball in camera video using computer vision. • **Position Tracking:** Drone follows ball autonomously by adjusting speed, altitude, and position based on the ball's flight path to keep the ball in the camera's frame. • **Landing Spot Identification:** Fly over to the ball once it stops moving, marking its location at rest by hovering overtop. • **Collision Avoidance:** Detect and avoid obstacles like trees, water, or sand (or walls). • **A Real-Time Tracker:** Provide accurate tracking and fast adjustments.	• **Sufficient Battery Life:** Capable of continuous flight for 2 hours per full charge to track golf balls throughout a typical 18-hole golf game minimising battery changes required [13]. • **Minimum Max Speed:** Must fly at ~150 MPH to keep up with golf balls, which are hit at speeds between 111 mph and 147 mph on average [14]. • **Image Segmentation Accuracy:** The algorithm must achieve an IoU score of at least 0.75 to accurately identify the golf ball. [15]. • **Image Processing/Capture Rate:** Software must process images at 10 Hz* and take images at 20 Hz* for real-time tracking of the golf ball. **Currently educated guesses, to be revised.* • **Robot Footprint:** Avoid obstacles within a 2-meter radius with 100% success.

Table 1. *Requirements Model with functions, objectives, and constraints.*

The critical design parameters for effective ball tracking include the camera's imaging rate, processing speed, and field of view. The camera must capture images quickly enough to track the ball's fast movement, while the processing speed must be able to handle these images in real-time. A sufficient field of view ensures the ball stays within the frame for continuous tracking. Balancing these factors is essential for optimal performance.

While the design parameters are essential, considering environmental and societal concerns is also important. Noise pollution could disturb other golfers, and drone malfunctions may result in debris and litter or disrupt local wildlife. Privacy issues could arise from unintended footage capture, and the cost of the technology could create accessibility barriers for some users. It will be important to have awareness of and discuss these concerns to create a responsible solution.

Design Strategy

Design Prototype Demonstration Plan: We aim to develop a drone that autonomously tracks a golf ball in flight, keeps it within the camera's frame of view, and hovers over the stationary ball once it lands, providing a visual marker for the golfer to easily locate the ball, as shown in *Figure 1*. To demonstrate this functionality, we will begin testing by gently lobbing a golf ball, ensuring the drone maintains visual tracking, moves closer as needed, and hovers over the ball. This controlled setup allows us to refine detection, tracking, and flight controls before progressing to faster throws and outdoor tests.

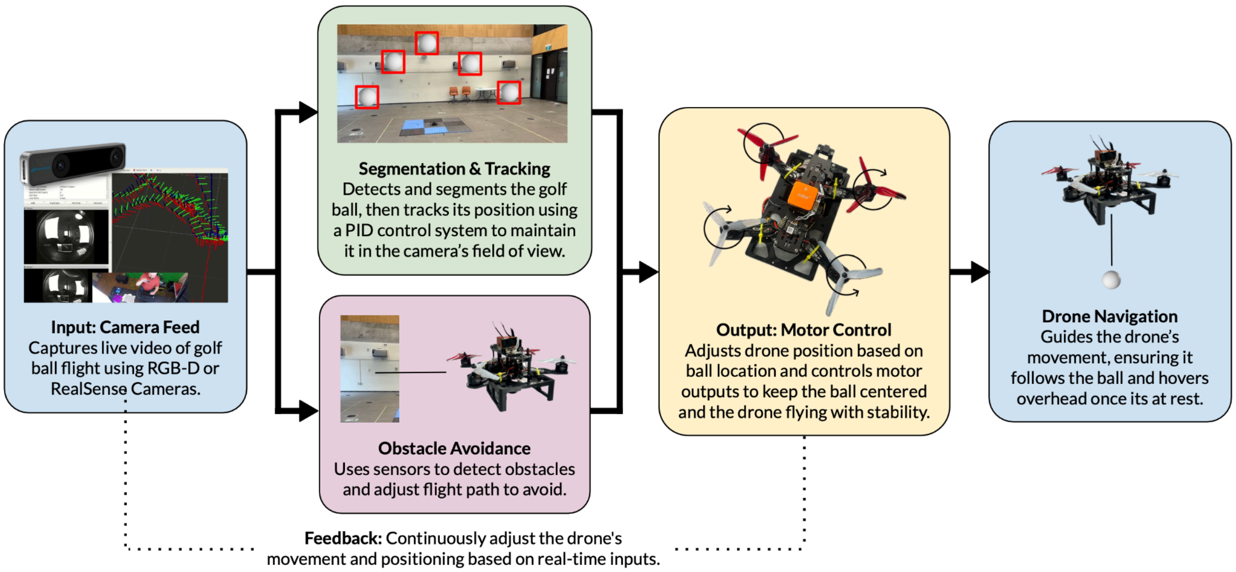

Figure 1. *Block Diagram conveys how different design components and stages will interact.*

To address our design problem, we will take a sequential and iterative approach, gradually building functionality on our drone to track golf ball flights in real-time. Incremental steps are given below.

Segmentation and Tracking in Software: Firstly, we will capture videos of moving golf balls in MY580 to create a dataset for segmentation training. We aim to explore several segmentation networks, including U-Net, YOLO, and DeepLabv3+ with various backbone architectures such as VGG-16, Resnet-50, and MobileNet to train a model that efficiently and accurately segments the moving golf ball in the captured video frames [15]. We will verify that the segmentation is robust and capable of handling variations in depth, trajectory, and colour deviations. By testing the model in software initially to ensure accurate segmentation, this will ensure that the drone can later maintain the ball in frame when the model runs on the Jetson Nano in real-time.

Visual Servoing (VS) and Drone Control: We plan to develop an Image Based (IBVS) or Position Based (PBVS) control loop where the drone uses the bounding box or image plane features to keep the ball centred in the RGB-D or RealSense camera's frame of view. This will likely involve a PID control system to adjust motor outputs based on deviations from the ball's trajectory.

Integration for Basic Tracking: Next, we will integrate the segmentation and control system to create basic tracking capabilities. This phase will involve testing the drone's ability to follow slower golf ball throws, starting with rolled balls and progressing to tracking balls in flight from a distance. The drone should hover overhead and follow the ball's XY trajectory until the ball comes to rest.

Obstacle Avoidance: In parallel, we will incorporate obstacle avoidance to prevent the drone from encountering hazards such as trees, water, or sand. This will likely involve using visual sensors like the RGB-D camera to construct point clouds which will be converted to a 3D occupancy grid with packages such as OctoMap [16]. Algorithms such as Trajectory Rollout can then be used to locally avoid obstacles while still being able to follow the ball. Testing will be done with obstacles in MY580 to proxy the real world.

Anticipated Tradeoffs: Due to the high speed of the golf ball, the drone's software must process images quickly to track it effectively. However, high-accuracy image segmentation models often have slower runtimes. As a result, we anticipate needing to tradeoff segmentation accuracy with processing speed, sacrificing some precision to ensure real-time tracking performance.

Mitigation Strategy: To minimize integration issues, we will establish clear coding conventions and test subsystems independently before combining them. For debugging, the drone will transmit segmented images to a laptop, allowing us to verify segmentation accuracy in real time. If we notice inconsistent or inaccurate segmentations, we can refine the dataset, apply augmentation, or explore other pre-trained models to improve performance. If the RGB-D camera or obstacle avoidance systems fall short, we will consider adding Time-Of-Flight sensors and pre-define obstacles in the testing environment. If hardware limitations or control system challenges occur, we will simplify ball-tracking scenarios (e.g. slower trajectories) and rescope to focus on core features, ensuring the drone can track and mark the ball's final location.

Verification, Validation, and Evaluation

A combination of verification and validation assessments will ensure that technical components operate safely and as intended while meeting the design goals and stakeholder requirements. Verification ensures the functional and mathematical correctness of our system using systematic testing. Validation ensures the system meets user needs by assessing tracking accuracy, reaction time, stability, obstacle avoidance, and final positioning. These are presented below in *Table 2*.

Verification	Validation
• **Simulations:** Visually verify the flight stability, visual tracking, and control algorithms using Gazebo and Rviz. • **Unit Testing:** Verify the functionality of individual subsystems, including computer vision, flight control, and object tracking (expected 90% detection accuracy). • **Integration test:** All subsystems interact with others without errors.	• **Final Position:** The drone's final position should deviate no more than 1 meter from the ball's final resting position • **Obstacle Avoidance:** Achieve a 100% success rate. No collisions. • **Tracking Accuracy:** Targeting an average IoU of at least 0.75 to ensure high overlap between detected and actual ball positions. • **Response Time:** Drone's response should be no slower than ~0.1 seconds. • **End-to-End Test:** Ensure all subsystems work together, with the drone autonomously detecting, tracking, and following the golf ball, achieving fewer than 25% tracking failures. The PID controller will be fine-tuned for minimal tracking error and an average response time under 0.1 seconds.

Table 2. *Verification and Validation Metrics and Justification.*

One factor to consider when evaluating system accuracy is the method for obtaining the ground truth ball position. A possible approach is triangulation, where multiple cameras record from different locations to calculate the ground truth. This method offers high accuracy but may still have discrepancies as an aggregated value. Additionally, since verification and validation occur indoors, factors like lighting variations and occlusions may still impact tracking performance. Despite these challenges, the system is expected to perform reliably within acceptable tolerances.

The requirements model and design strategy we've outlined will guide our efforts toward successfully achieving our goals, and we're hopeful we'll be able to achieve them.

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