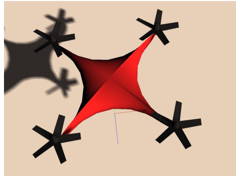
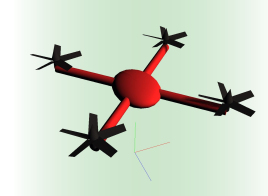


Computational design of soft body drones



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Abstract

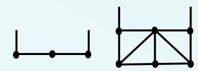
This project explores the power of computation in the area of customized drone design, specifically drones built with soft materials. The goal is to create an **effective computational way to accurately simulate and control soft-body drones**. In this project, tetrahedron mesh and the finite element method are used to model and simulate 3D drones. The linear quadratic regulator is used to control the drone so that this dynamic system is operated at a minimum cost.

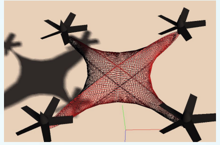
Introduction

Previous research in the field is mainly focused on designing drones that are built with hard materials. However, this project aims to devise new computer programs to design drones with morphable shapes, foldable structures, and assemblable functionalities. The main difficulty of controlling soft drones is **the uncertainty and instability of the movement of the drone**. To overcome this problem, we used the following methods.

Methodology

Geometry and Material Modeling:





The drone is built in 1D, 2D, and 3D spaces and used **linear mesh**, **triangle mesh**, and **tetrahedron mesh** respectively. The position of the mesh is updated using the finite element method, and the positions and directions of the rotors are updated through finding the normal vectors of the pieces of mesh where the rotors are located at. The information is then passed to the linear quadratic regulator in order to find the optimal thrusts to balance the drone. The thrust is then applied to the drone so that the drone is stabilized.

Physics Simulation:

We developed several methods to build the simulation, such as the mass-spring model and **the finite element method (FEM)**, and found the later performs better in 3D. FEM has become a popular approach to solving problems in continuum mechanics. The finite element method breaks down continuous volumetric bodies into finite elements—in this case, tetrahedrons. Calculations are then applied each tetrahedron and used to approximate what is taking place for all points inside each tetrahedron. The finite element method is used to calculate the **elastic force on each particle caused by deformation**; it makes use of a neo hookean model of hyperelasticity and has Lamé coefficients that fall within the range of those of a standard silicon rubber.

Feedback Control:

We first implemented the proportional–integral–derivative controller (PID) and later developed a better method, **the linear quadratic regulator (LQR)**, which is likely the most important result in optimal control theory to date. It returns **the optimal thrusts based on the current state**. Given a linear system

$$\dot{\mathbf{x}} = \mathbf{A}(\mathbf{x}-\mathbf{x}^*) + \mathbf{B}(\mathbf{u}-\mathbf{u}^*)$$

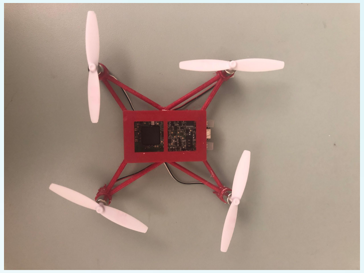
where **x** is the state vector, containing information of current position and Euler angles, as well as their derivatives, **u** is the control vector, representing the thrusts for individual propellers, and **A** and **B** are matrices related to the current geometry of the drone and position and direction of the rotors.

The infinite-horizon cost function is given by

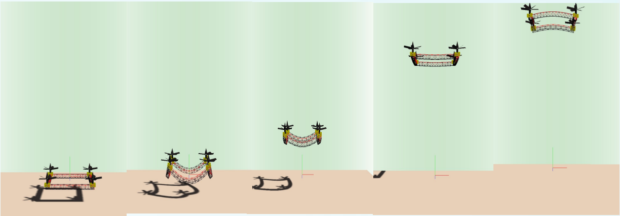
$$J = \int_0^\infty [\mathbf{x}^T\mathbf{Q}\mathbf{x}+\mathbf{u}^T\mathbf{R}\mathbf{u}]\, dt,\ \mathbf{Q} = \mathbf{Q}^T \geq 0,\ \mathbf{R} = \mathbf{R}^T > 0$$

To find the optimal cost-to-go function $J^*(\mathbf{x})$, we use Hamilton–Jacobi–Bellman equation and write it in the form $\mathbf{x}^T\mathbf{S}\mathbf{x}$. Due to the convexity of its HJB form, the minimum can be found by setting the gradient to 0. This yields the optimal policy $\mathbf{u}^* = -\mathbf{R}^{-1}\mathbf{B}^T\mathbf{S}\mathbf{x}$. Inserting this equation back to the HJB form, we find **S**, thus the optimal thrusts **u**.[1,2]

Results



A 3D-printed soft drone using TPU 95A



*These simulations are run with the PID controller and the mass-spring model

Conclusion

The next step of the project is to further optimize the control of drones by implementing **Reinforcement Learning** techniques. Meanwhile, the **3D printed soft-body drone** will be used to test the control beyond just the computer simulation.

References

1.Du, Tao, et al. "Computational multicopter design." (2016).
2.Russ Tedrake. Underactuated Robotics: Algorithms for Walking, Running, Swimming, Flying, and Manipulation (Course Notes for MIT 6.832).

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