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Drone Cage Design and Implementation to Enable Small Drone Architecture Testing

Marco Fagetti
Embry-Riddle Aeronautical University

Emily M. Suh
Embry-Riddle Aeronautical University

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Marco Fagetti*, Emily M. Suh**

Embry-Riddle Aeronautical University, Daytona Beach, FL, 32114

Abstract

Geometric mechanics is a dynamical formalism that allows for simultaneous treatment of rotational and translational motion without the drawbacks of attitude parameterization sets. While geometric mechanics is well suited to deal with full six degree-of-freedom motion or significant position-attitude coupling, this formalism has yet to be extensively applied to hardware systems. The broader research goals of this work aim to prove the practical viability of this theoretical framework by applying it to a class of Crazyflie drones, which are frequently used to assess Guidance, Navigation, and Control schemes. To efficiently achieve these goals, a reliable, collapsible drone cage is required to conduct such experiments in. As a result, the team has designed and constructed a modular cage that can be used to safely test drone behavior. Requirements from the drones' suite of hardware necessitate a cage with dimensions of 3m × 3m × 7m, a fact which drove the collapsible nature of the design. Given the cage's modularity, its size can be further scaled for future experiments. The work here discusses the construction and development methodology of the cage, and preliminary results for a path-tracking simulation illustrate how the cage and Crazyflie hardware interface provide accurate truth-data.

*Undergraduate Student, Aerospace Engineering
**Undergraduate Student, Aerospace Engineering

I. Introduction

The geometric mechanics framework is a convenient dynamical formalism that allows for simultaneous treatment of rotational and translational motion without the drawbacks inherent in attitude parameterization sets. Many Earth-based systems do not encounter issues with these parameterization sets as full, unimpeded six degree-of-freedom motion is not achieved, whether due to gravity, drag, or system limitations. However, space-based applications often will be in environments where such free motion is possible. The geometric mechanics framework is well suited to deal with these situations. However, this formalism, while theoretically rich, has yet to be applied to hardware systems in an appreciable way. This project aims to prove the practical viability of this theoretical framework by applying geometric mechanics to a class of small drones. These Crazyflie drones are used extensively in research institutions to assess the validity of Guidance, Navigation, and Control schemes. The research team has twenty Crazyflie drones, two ground stations, and a myriad of different associated hardware for use with the drones.

Figure 1: Ground vehicle (left) and Crazyflie drone (right).

Requirements from the Crazyflie suite of hardware, namely the LocoPositioning Deck which provides data on the system state, necessitate a large cage with dimensions 3m × 3m × 7m [1]. A smaller version of this cage (with dimensions 1m × 1m × 1m) was developed. Scaling this first module up necessitated additional PVC pipes and fittings, netting or screening, hooks, and grommets. Several iterations and trade studies were required for the successful development of the full-scale cage. Given the cage's modular nature, it can be scaled up to increasingly larger sizes, should the need arise in the future.

II. Drone Cage Construction Process

An initial 3-dimensional, computer-aided design of the drone cage was first created and rendered with Autodesk Inventor to establish an ideal final design of the cage and to determine the material requirements and specifications for construction. Following the suggested instructional guide from the creators of the Crazyflie drones, the drone cage was designed to be a maximum of 3m × 3m × 7m in size. For storage, construction, and customization purposes, the drone cage was also designed to be collapsible and modular. The maximum potential size of the drone cage and its collapsible and modular characteristics were taken into consideration when choosing the appropriate materials and components with which the cage would be constructed.

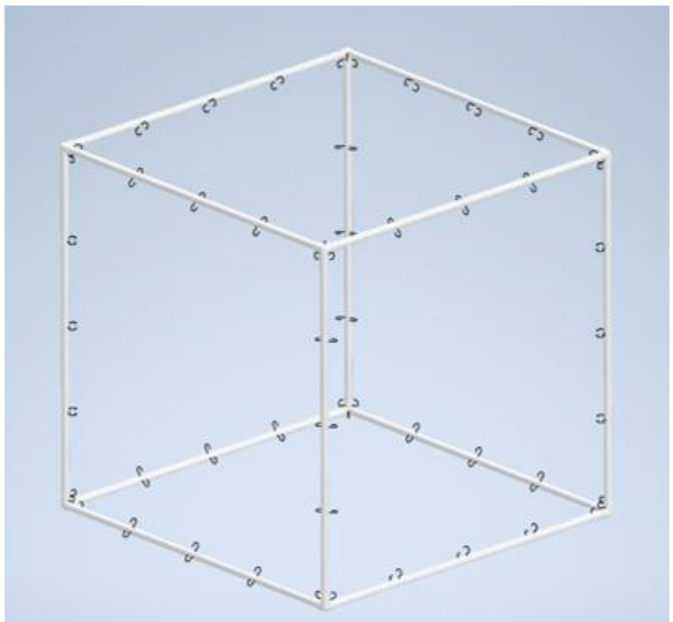

Figure 2: A 1m × 1m × 1m CAD model of the drone cage.

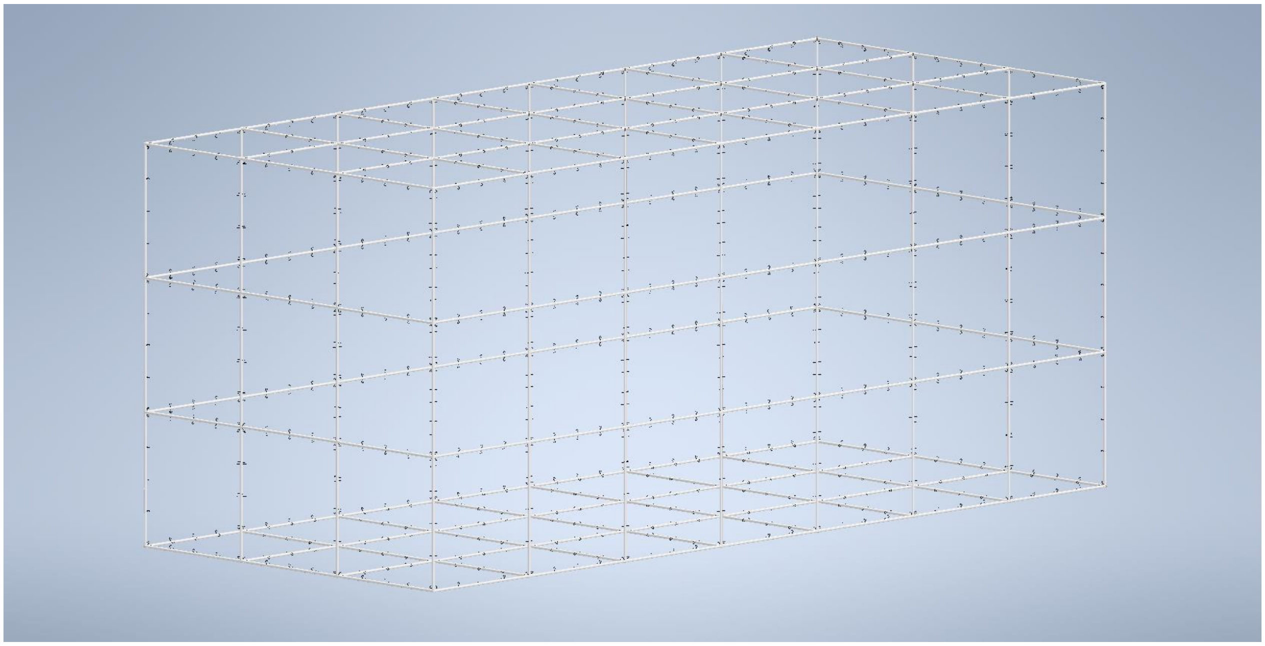

Figure 3: CAD model of the drone cage at its maximum size.

A lightweight and sturdy material was required for the skeletal frame of the cage. At its maximum size, the cage would be subjected to large structural stresses, which would require a frame that can support these stresses and strains without buckling or collapsing. However, materials such as aluminum, steel, or titanium beams that have a high maximum stress tolerance are too great in density for practicality and collapsibility and too expensive for the given budget. To meet these requirements, ½ inch Schedule 40 PVC pipes are deemed the best fit. PVC pipes are overall cheaper than metal beam/tubes while still providing sufficient structural support to prevent structural failure. PVC pipes are also lightweight and easily modified. Using PVC pipes also allows PVC fittings to be used to connect the pipes instead of requiring the tools and skills for welding, screws, nuts, and bolts with metal materials. The three types of PVC fittings used are shown below.

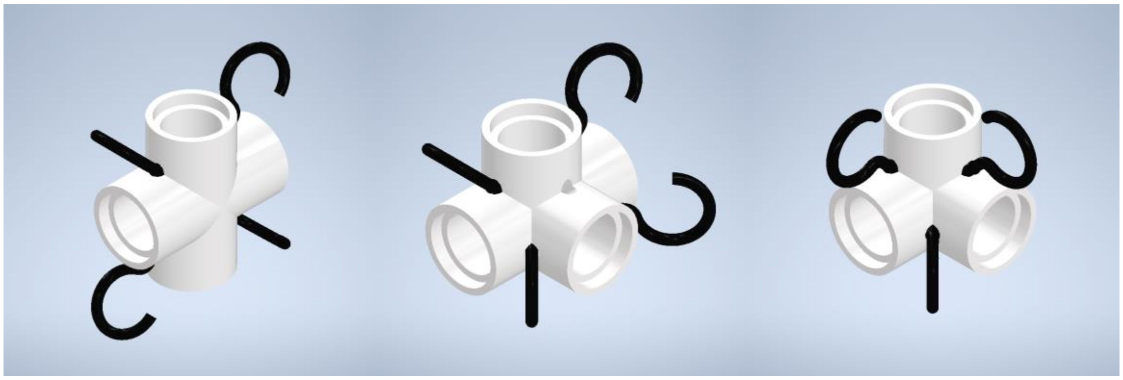

Figure 4: CAD models a 4-way PVC cross fitting (left), a 4-way PVC tee fitting (center), and a 3-way PVC elbow fitting (right) with inserted hooks.

To enclose the skeletal frame, netting was required on each 1mx1m square face. Multiple considerations were made when selecting an appropriate material for this interface. First, the material must be transparent enough to see the drones inside the cage. In addition to this, it must be lightweight so as to prevent structural failure and heavy loading on the PVC frame. Also, the netting mesh must be small enough such that the drones do not get caught in the mesh. Given the resources readily available, the best option was outdoor screening often used for windows and doors. This material provides a dynamic solution to the multiple requirements.

Upon the decision to use screens for the cage enclosure, a solution was required for their attachment to the PVC structure. The initial idea of a hook/grommet combination was attempted on a 1mx1m module. For each PVC pipe, six hooks were attached so that a screen could be attached on two sides per pipe. Each 1mx1m screen required 12 holes with grommets – three on each side. Simply cutting holes and attaching grommets straight onto the screens revealed the screens possible point of failure due to tearing around the holes, especially when the screens were stretched in tension. Thus, reinforcements to each edge of each screen had to be made. Similar considerations were made for the selection of materials for this reinforcement compared to the netting material selection. The best choice was canvas drop cloth, as it provided adequate reinforcement and strength under tension while remaining lightweight. To attach this material to the screens, different approaches were taken before deciding on the final method.

Determining a method of attachment for the canvas drop cloth proved to be one of the greater challenges in designing the cage. Several ideas including sewing and iron-on hemming tape were considered; however, neither was practical or efficient in the construction of the cage. Instead, the canvas drop cloth was attached using staples. In testing the efficacy with the 1mx1m module, staples proved to be practical and less time-consuming while still providing a reliable fastening between the cloth and the netting.

The preparation of all the cage components took 15 weeks to complete, from August 2021 until December 2021. All PVC pipes were cut to the appropriate length to create a 1m x 1m unit cell. A straight line was then drawn along the length of each pipe to obtain a point of reference when marking the locations along the pipes in which the hooks would be screwed. To accurately mark four points exactly 90 degrees apart around the outer circumference of the pipes, two custom 3-D printed blocks with four prongs were created. Each block contained a circular hole with a diameter equal to the outer diameter of the pipes, and each prong was spaced 90 degrees apart around the center of this hole. The block would comfortably, but tightly, slide onto the pipe, where one prong would be aligned with the line that was drawn earlier. The three other prongs would then serve as a guide showing where to mark the pipe for the potential screw holes. This process was repeated 3 times per pipe for each pipe. After all the PVC pipes are marked, holes are drilled in all 12 marked locations on all the pipes. For the installation of the hooks into the pipes, the maximum number of pipes that would be located along the edge of the drone cage was calculated. For a 3m × 3m × 7m cage, 52 1m pipes are placed along the edge, so only those pipes require 3 sets of 2 hooks placed 90 degrees apart. All other pipes have 3 sets of 2 hooks installed 180 degrees apart. For each of the fittings, holes are drilled in each of the corners, where the hooks are installed.

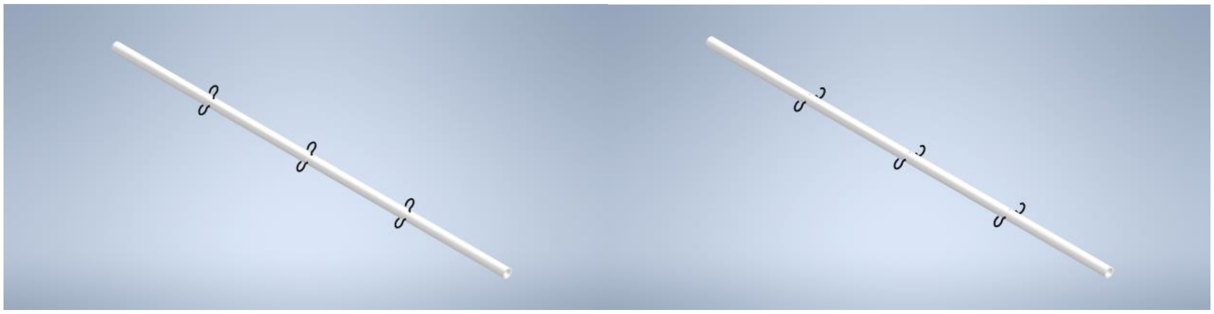

Figure 5: CAD models of PVC pipes for the corner edges of the drone cage (left) and for the center linings of the cage (right).

The preparation of the screens took several steps to accomplish. The 102 individual squares of netting were first cut into the appropriate dimensions from the several rolls of netting acquired. Meanwhile, the canvas drop cloth was cut into long strips that would be later attached on each edge of the screens. Once the netting and cloth were cut and prepared, staples were used to attach a strip of cloth that wrapped around each edge of each screen. After attaching the cloth to the netting, a pipe with hooks installed is placed along the edges so that the location of where the grommets need to be installed is marked on the cloth. A grommet hand press machine is then used to install three grommets along each edge and one grommet in each corner.

Figure 6: Rolls of fabricated netting with canvas-cloth lined edges and grommets.

III. Results

The construction of the drone cage brought to light several bottlenecks that were encountered in the manufacturing process. The amount of manpower available throughout the process was a prevalent limiting factor that reduced the potential progression rate. Any tasks that were simple yet tedious, such as screwing all the hooks into the PVC pipes, were overcome by creating an assembly line of several volunteers. In the preparation of the PVC pipes, the accuracy of the hook placements was of great importance as it would affect the placement of the screen. Requiring accuracy and consistency among all the pipes, a marking tool that would allow the user to accurately and precisely mark each potential hook placement around the pipes approximately 90 degrees apart was designed and 3D printed. The attachment of the canvas drop cloth to the square cuts of netting was another bottleneck that reduced the rate of production. The process required one person to attach the cloth strips to the netting squares with the staples and create incisions where the grommets would be placed while a second person inserted the grommets into the cloth. During the construction process, the edges of the cloth strip showed signs of fraying, so the person in charge of inserting the grommets also needed to remove the frayed ends, which increased the workload and further impeded the rate of production.

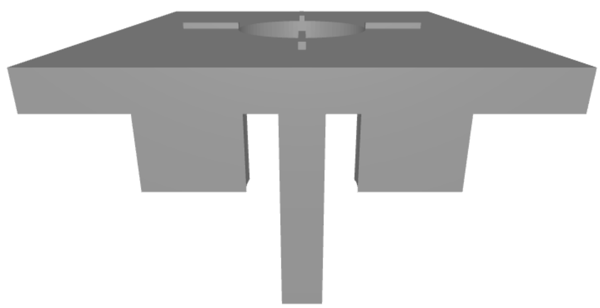

Figure 7: CAD model of the 3D printed marking tool used to mark the drilling locations along the pipes.

The drone cage has been successfully constructed to its maximum size. Although the cage did display signs of bending along the sides, there was no buckling or structural failure after complete assembly. All measurements of the cage's components were proven correct as minimal issues were encountered during the assembly. The cage's modular design also successfully allows for smaller variations of the constructed cage.

Figure 8: A 2m x 2m x 2m constructed model of the drone cage.

Figure 9: Fully constructed drone cage at its maximum size.

IV. Future Improvements and Implementations

The final construction of the cage provided insight into possible future failure points in the cage as well as improvements that may be made to prevent failure and increase the overall durability and longevity of the cage. Although there was no structural failure, significant bending of the skeletal frame was present along the center of the roof of the cage and along the 3mx7m sides of the cage. This was to be expected as they are locations with low structural support and high structural loads. Several proposals have been considered to remedy this. Support beams or columns made of either wood, aluminum, or PVC pipes with a small cross-sectional area can be added inside the cage. They would be placed in key locations that would provide maximum additional support with as few columns as possible to minimize the level of obstructions during drone flights and experimentation. Another proposal involves thin aluminum rods with a diameter smaller than the inner diameter of the PVC pipes that make up the cage's skeletal frame. Several rods would be placed inside the pipes to improve the structural integrity of the cage without drastically increasing the structural loads due to the weight of the cage itself. This would also avoid introducing obstacles inside the cage that may interfere with experiments and damage the drones when in flight. The cloth that reinforces the edges of the screens showed fraying during construction. While this does not pose any immediate need for concern, it is important to consider future repairs.

V. Conclusion

In order to verify the practical viability of the geometric mechanics framework, a drone cage was constructed to be a reliable, collapsible, and adjustable controlled space for the experimentation of this framework with Crazyflie drones. The cage is designed in a modular format that allows for the adjustment of the cage's size for varying experimental conditions. With a skeletal frame made of PVC pipes and PVC fittings, the cage is light in weight while still maintaining relatively sufficient structural strength. The screens are designed to be easily attached and to the frame and create a barrier that can protect the users from possible loss of control of the drones as well as securely contain the drones within the cage without risking possible damage to the drones when contact is made. The preparation and construction of the drone cage encountered several bottlenecks that required temporary increases in personnel and innovative tools to ensure the cage was built at a reasonable rate and accuracy.

The final assembly of the cage at its maximum size validated and verified the integrity of its design, called attention to any necessary repairs, and provided insight into future improvements. In order to efficiently and safely assemble and disassemble the drone cage, a minimum of 6 people is recommended to avoid injuries to the people and damages to the cage. The cloth edges of the screens showed signs of fraying and will require a solution to avoid future fraying and continual maintenance. As the cage's size was increased, there was less structural support towards the center of its ceiling, and its sides were subjected to larger axial loads. Therefore, some initial bending was visible on its longer lateral sides. Future reinforcement of these areas may be necessary and has been considered.

VI. References

[1] *Getting started with the Loco Positioning System*. Bitcraze. (n.d.). Retrieved August 20, 2021, from https://www.bitcraze.io/documentation/tutorials/getting-started-with-loco-positioning-system/