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Flight Trajectory Simulation of Robotic Throwing Shuttlecock

Fuwen Hu, Qinghua Liu, Jingli Cheng, Yunhua He *

***Abstract*—The theme of the ABU Asia-Pacific Robot Contest in 2018 is to throw the shuttlecocks through the provided rings at height. The shuttlecock is an object made of cotton balls or filled with rice husks, symbolizing prosperity and happiness. For the design and control of robotic throwing mechanism, two aspects of research need to be carried out: selection of initial throwing parameters, aerodynamic behavior of shuttlecocks. Firstly, the influence of the initial throwing speed and the throwing angle on the throwing distance was studied through the kinematics simulation analysis, and the design of the throwing trajectory was further studied. In addition, the influence of air resistance on the flight trajectory was also studied. Finally, for the precise control parameters of the throwing mechanism, the rigid-flexible coupled multi-body dynamics simulation analysis was performed using ADAMS(Automatic Dynamic Analysis of Mechanical Systems) virtual prototype technology. The shuttlecocks throwing experiments conducted on the playing field showed that the design and simulation analysis of the throwing trajectory played a good guiding role in the design and development of the shuttlecocks throwing robot.**

I. INTRODUCTION

From ancient Greek-Roman throwing machines [1]to today's transport-by-throwing [2],accurate throwing of projectiles is a well-known robotic task. To obtain high a desired target task (position and orientation), (i) flightpath design of the throwing based on dynamical consideration, and (ii) robust controller design that realizes high accuracy for tracking of the manipulator along the expected trajectory, are regular methods[3]. For transportation of small-sized rigid objects in industrial environment, Mironovet al.[2] a sample-based algorithm for trajectory forecasting. For throwing an object by a robot system in unmanned environments, Okada et al. [3] introduced a sensitivity analysis of the landing point with respect to model uncertainties (uncertainty of initial position and joint Coulomb friction), and design the optimal throwing trajectory that minimizes the sensitivity. For a robotic arm to perform a throw task of an object to reach a goal target, Sintov et al. [4] presented a novel offline method for finding an optimal solution for the throw motion taking the kinodynamic [5] constraints into account. The key concept of this algorithm is parameterizing an analytic trajectory function. Using dynamic movement primitives as the underlying motor representation, Gams et al. [6]described an optimization approach that enables the generation of a new motion trajectory for a robotic throwing task where the location of the target is determined by a stereo vision system. To create more flexible movement for table tennis, Koç et al. [7] used a free-time optimal control approach to derive two different trajectory optimizers. For the catching of thrown objects, Mironov et al. [8] developed a predictor based on nearest neighbor regression, which does not require exact physical model of the motion. Uzzaman et al. [9] designed a stationary throwing robot and performed some geometrical analysis to determine the throwing destination. Gayanov et al. [10] proposed a combined forecasting algorithm where the deterministic motion model for each trajectory is generated via the genetic programming algorithm. Frank et al. [11] put forward a bio-inspired technical approach for the fast transportation of objects thrown by a throwing device and caught again by a catching device. Ritz et al. [12] presented a method for enabling a fleet of circularly arranged quadrocopters to throw and catch balls with a net.

The research background of this article is ABU Asia-Pacific Robot Contest in 2018 [13], the competition theme of which is to throw the shuttlecocks through the provided rings at height, i.e. "Dragon Shuttlecock". Undoubtedly, the competition task is very comprehensive. However the core of robotic design is the precise and fast throwing of shuttlecocks.

This article is organized in the following way. In the second section, the influence of the initial throwing speed and the throwing angle on the throwing distance was studied through the kinematics simulation analysis, and the design of the throwing trajectory was further studied. In the second section, for the precise control parameters of robotic throwing mechanism, the rigid-flexible coupled multi-body dynamics simulation analysis was performed using ADAMS virtual prototype technology.

II. FLIGHTPATH DESIGN OF ROBOTIC THROWING SHUTTLECOCK

A. Physical Characteristics of Throwing Shuttlecock

The heart and soul of ABU Asia-Pacific Robot Contest in 2018 is the shuttlecock. The shuttlecock is an object made of cotton balls or filled with rice husks, symbolizing prosperity and happiness. The flying shuttlecock depicts a flying dragon, iconic of human power and the universe. As shown in Fig.1, shuttlecock is made of soft material (natural fiber or synthetic fiber) and is attached by Tail and Fringe. Specific requirements [13] for the shuttlecocks of ABU Asia-Pacific Robot Contest in 2018 are listed as follows:

- **Material**: soft material (natural fiber, or synthetic fiber);
- **Weight**: from 60 to 100 gram including shuttlecock, tail and fringe;
- **Shape**: sphere, minimum 120 mm diameter; or other shapes nearly sphere with minimum120 mm dimension when measured from any angles and through the center of shuttlecock.
- **Tail**: Different colors. Maximum thickness 10 mm. Automatic Robot holds the tail from Keeping Point (with distance to Shuttlecock 250mm) or further.
- **Fringes**: Different colors with minimum 3 colors. Minimum 5 Fringes. Fringes are freely attached to different positions on Shuttlecock. The length of Fringes is minimum 200 mm starting from the bottom of Shuttlecock.

Each team has two robot of: one manual robot and one automatic robot or two automatic robots. Only one automatic robot is allowed to throw shuttlecock. When a game starts, manual robot will pick shuttlecocks and handle it to automatic robot. After receiving the shuttlecock, automatic robot will move into throwing zone and throw the shuttlecock at the ring. If the shuttlecock goes through the ring successfully, points will be given.

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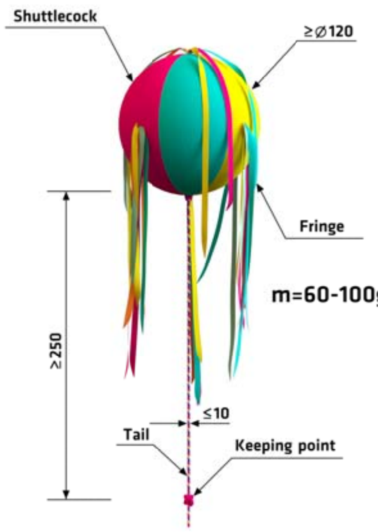

Fig.1. Physical characteristics of throwing shuttlecock

B. Mathematical Modeling of Throwing Motion

According to the basic principle of slanting motion, as illustrated in Fig.2, the relationship between the projectile distance S, the throwing speed v_0, the throwing angle θ, and the throwing height h can be expressed as the following formula,

$$S = \sqrt{\frac{2hv_0^2\cos^2\theta}{g} + \left(\frac{v_0^2\sin 2\theta}{2g}\right)^2} + \frac{v_0^2\sin 2\theta}{2g} \tag{1}$$

where g represents the acceleration of gravity, and the value is$9.8\text{m}/s^2$.

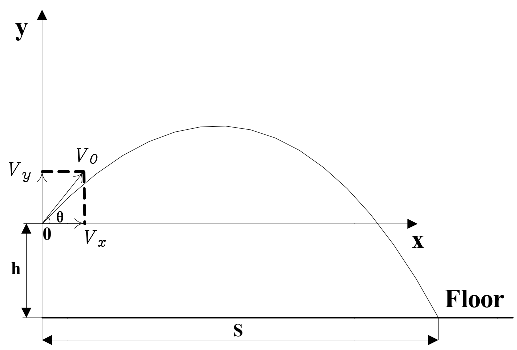

Fig.2. Throwing motion

Obviously, when the throwing structure of the designed throwing robot is determined, the initial throwing height h is determined. Thus we can determine the optimal throwing speed v_0 with (1) and the projectile distance S. According to the requirements of the "Dragon Shuttlecock" contest, the initial throwing height h should not exceed 1.8m, here set h as 1.6m, then the surface image of the projectile distance S with the throwing speed v_0 and the throwing angle θ can be figured out as Fig.3 using Matlab program. From the surface image, it can be seen that the projectile distance S is greatly affected by the throwing speed v_0 and the throwing angle θ. With the same throwing angle θ, the projectile distance S increases as the throwing speed v_0 increases. However with the same throwing speed, when the throwing angle θ varies from 0 to 45 degrees, the projectile distance S increases, and when the throwing angle is greater than 45 degrees, the projectile distance S decreases as the throwing angle θ increases. That is to say, 45 degrees of the throwing angle is a critical value.

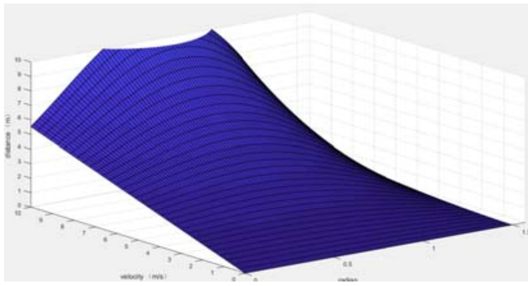

Fig.3. Relationship of projectile distance with throwing velocity and throwing angle

C. Flightpath Design through the Provided Rings

According to the requirements of the "Dragon Shuttlecock" contest, the thrown shuttlecock must pass through the provided ring and fall on the target plate before it can be considered as a victory. This means that the initial throwing point, the center of the provided ring, and the center of the landing plate are best on the parabola flightpath of thrown shuttlecock. There are three candidate strategies for shuttlecock through the provided ring. Option 1: The shuttlecock passes through the provided ring at the highest point of parabola flightpath (Fig.4-a). Option 2: The shuttlecock passes through the provided ring when it falls at the highest point. (Fig.4-b). Solution 3: The shuttlecock passes through the provided ring before it rises to its highest point (Fig.4-c).After calculation, Option 1 and Option 3 cannot meet the requirements of the competition, and Option 2 is adopted.

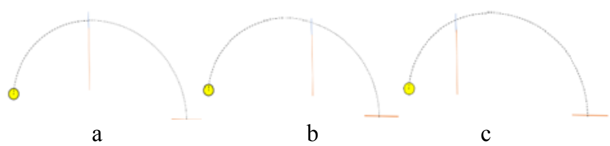

Fig.4. Candidate strategies for shuttlecockthrough the ring

D. Effect of Air Resistance on Flightpath

As shown in Fig. 5, the resistance of air to the shuttlecock can be mainly divided into frictional resistance and differential pressure resistance [14]. Frictional resistance is the air friction formed due to the viscosity of the air when the air flows through both sides of the object; the differential pressure resistance is the pressure difference related to the flow formed against the front and back surfaces of the object. This relationship is directly related to the shape of the object and the speed of movement (laminar flow, or turbulent flow). These two resistances will be due to the shape of the object at the same speed. There are considerable differences. After considering resistance, the differential equation of throwing shuttlecock motion is the following (2). k is the air resistance coefficient. When the sphere radius of the shuttlecock is 0.06 m, the value of k is 0.03.

Then we use Matlab software to solve the above differential equations(2). After repeated introduction, the optimal projection trajectory can be obtained when the initial speed is 10.8 m/s and the throwing angle θ is 40 degrees. For clear analysis, we have given the flightpath of the shuttlecock (Fig.6), the velocity image (Fig.7), the time-varying angle between the speed direction and the horizontal direction (Fig. 8) when there is air resistance and air resistance is not considered.

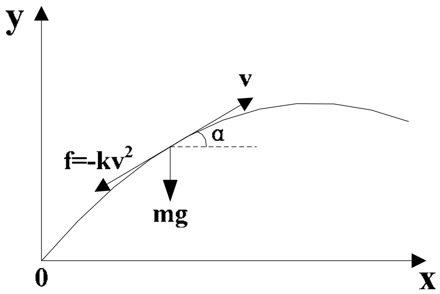

Fig.5. Force analysis of thrown shuttlecock

$$\begin{cases} -kv^2cosa - m\ddot{x}^2 = 0 \\ -mg - kv^2sina - m\ddot{y} = 0 \\ sina = v_y/vcosa = v_x/v \\ \ddot{x} = -(k/m) \times \sqrt{(\dot{x})^2 + (\dot{y})^2} \times \dot{x} \\ \ddot{y} = -(k/m) \times \sqrt{(\dot{x})^2 + (\dot{y})^2} \times \dot{y} - g \end{cases} \tag{2}$$

Here assuming initial conditions,

$$\begin{cases} x_0 = 0 \\ y_0 = 1.6 \\ \dot{x}_0 = v\cos a \\ \dot{y} = v\sin a \end{cases} \tag{3}$$

According to Fig.6,taking into account the air resistance, the landing time of the thrown shuttlecock becomes smaller, the projectile height decreases, the projectile distance becomes shorter, and the flightpath is no longer a parabola.

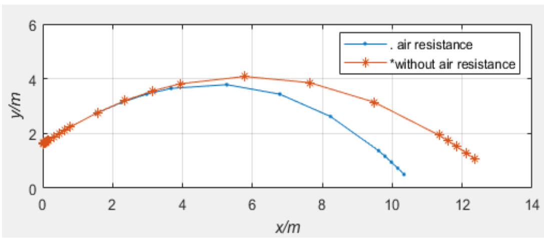

Fig.6. Flightpath with VS. without air resistance

From Fig.7,when there is air resistance, the speed of the thrown shuttlecock decreases more quickly.

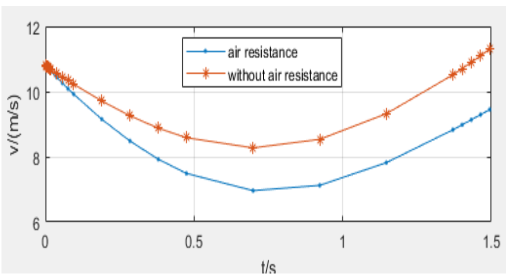

Fig.7. Flight velocity with VS. without air resistance

As can be seen from Fig.8, if we do not consider the air resistance, when the thrown shuttlecock rises or falls to the same height, the speed direction is equal to the horizontal angle, and they are symmetrical about the highest point. This symmetry is destroyed when air resistance is considered.

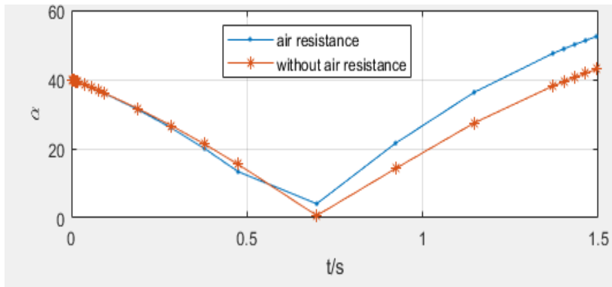

Fig.8. Time-varying angle with VS. without air resistance

E. *Robotic Throwing Mechanism*

The mathematical modeling of the thrown shuttlecock provides basic data for designing the robotic throwing mechanism. In order to obtain sufficient kinetic energy or initial speed, we use the cylinder to provide the driving force to push the throwing arm to swing the gripper (Fig.9). The cylinder model is CDM2B20-125, and the diameter of the cylinder is 20mm, the stroke is 125mm.The projection rod requires strong rigidity and light weight, so carbon fiber rods are used as the projection arm. During the swinging process, the speed of the shuttlecock increases rapidly, and the generated centrifugal force would overcome the friction between the gripper and the shuttlecock tether, and the hydrangea is thrown out accordingly.

Fig.9. Throwing shuttlecock robot

In the robot manufacturing process, in order to speed up the task, we applied 3D printing technology [15,16] to print parts such as servo motor bearings. In order to accurately control the driving air pressure, we designed and developed an electronic pneumatic control valve. The electronic air pressure control valve first reads the analog value of the barometer, and then drives the servo motor to adjust the air pressure to reach the preset value. The control accuracy of this air pressure control method is about 0.05 Pa, which is a typical PID control [17]. This work only focuses on the design of the throwing mechanism of the robot. In addition, the key technologies of the competition robot include mobile robot positioning and navigation [18], automatic transferring shuttlecock technology and so on.

III. RIGID-FLEXIBLE COUPLED MULTI-BODY DYNAMICS SIMULATION ANALYSIS OF THROWING MOTION

A. Rigid-flexible Coupled Multi-body Dynamics Modeling

According to the previous analysis, the throwing highest point and the projectile distance of the thrown shuttlecock depend on the initial throwing speed and the throwing angle. In terms of the designed robotic throwing mechanism, the factor that affects the throwing speed is mainly the air pressure value of the cylinder, and the factors that affect the initial throwing angle include the gripping angle, the initial angle of the throwing rod, the length of the tether, etc. In order to accurately throw and control the shuttlecock, here we further apply the virtual prototyping modeling simulation software ADAMS to perform rigid-flexible coupling multi-body dynamic analysis [19,20].

Because the rope is a flexible body, it is easy to deform. When modeling, multi-section cylinders are used instead, and the joints is connected with a shaft sleeve (Fig.10). Cylinders and constraints are established by editing commands. The tether has vibration, deformation, and other dynamic characteristics in the actual process, and the use of bushings can add rigidity and damping coefficient to it. Therefore, the actual dynamic performance simulation of the tether can be truly reproduced by controlling its stiffness and damping coefficient values. Other analysis settings are relatively simple and are omitted here.

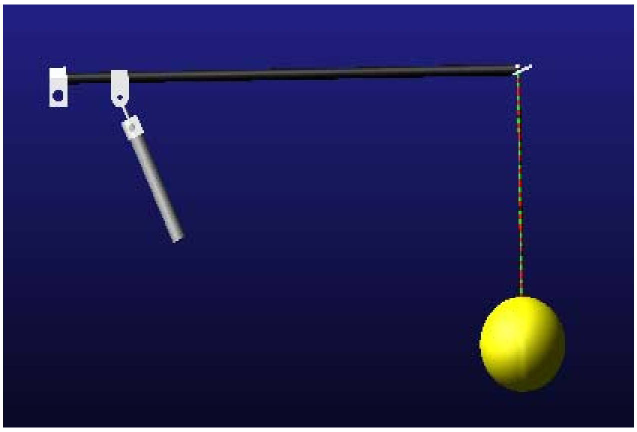

Fig.10. Modeling of robotic throwing mechanism

B. Motion Simulation and Result Discussion

In the working state of the projection mechanism, the main simulation cylinder will lift the projection wall as a whole and throw out the motion of the hydrangea. Set the simulation time to 2s and the step size to 500. Next we analyze the post-processing results.

- Influence of the gripping angle on projection angle

First, control other conditions unchanged, only change the gripping angle, and then set the angle of 20 degrees /25 degrees / 30 degrees /35 degrees, and the simulation results are shown in Fig.11. Obviously, it can be seen that the gripping angle is positively correlated with the initial projection angle. As the gripping angle increases, the projection angle also increases, causing the vertical velocity component v(y) to rise while the horizontal velocity component v(x) to decrease.

- Effect of rope length on projection angle

In the range of 240mm~300mm, change the length of the hydrangea tether with a difference of 30 and other conditions remain the same. It can be seen from the simulation results in Fig.12. That v(x) increases with the length of the tether, increases by 0.5 m/s, and v(y) decreases slightly with the length of the tether. And the initial angle of projection decreases with increasing tether length.

- Effect of initial angle of projection bar on projection angle

The angle of the initial projection bar is changed by a difference of 10 degrees, and the other conditions are unchanged. It can be seen from the simulation results in Fig. 13 that v(x) increases with the increase of the angle of the projection rod, and the increase is 2m/s. v(y) decreases with the increase of the angle of the projection rod, and the projection angle decreases as the angle of the projection rod increases.

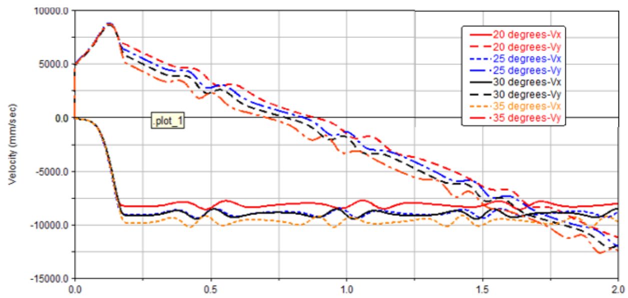

Fig.11. Influence of the gripping angle on projection angle

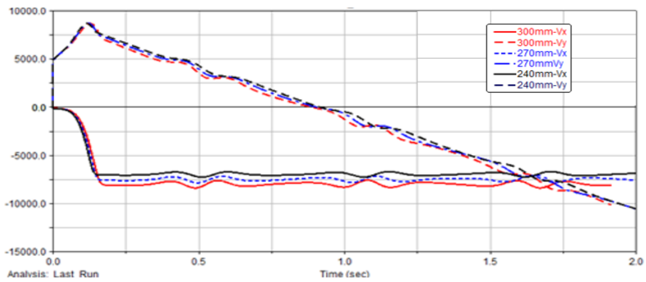

Fig.12. Effect of rope length on projection angle

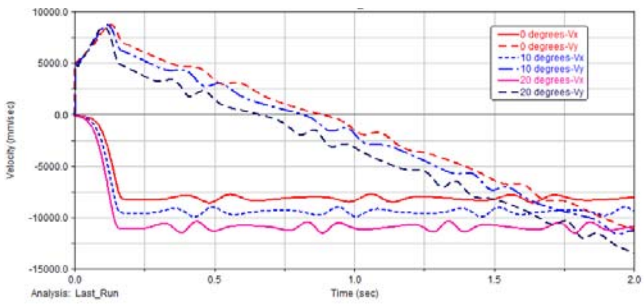

Fig.13. Effect of angle of the initial projection bar on projection angle

C. Optimal Control Parameters

Through several simulation experiments, the optimal control parameters are determined as the cylinder force 145N, gripping angle 20 degrees, the initial projection rod angle 0 degree. And the optimal trajectory is shown in the Fig.14. The best flight speed is shown in the Fig.15.

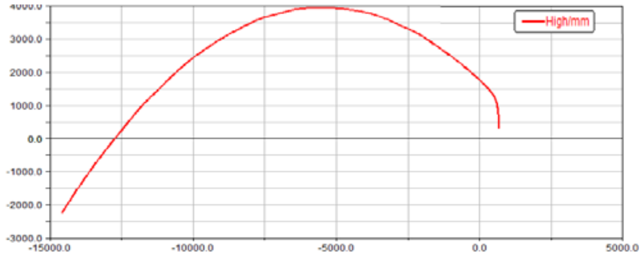

Fig.14. Optimal flightpath

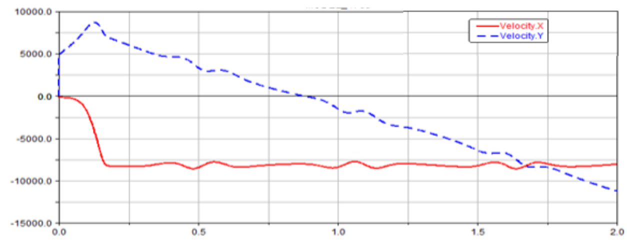

Fig.15. Optimal flight speed

IV. Experimental Test

After the optimal control parameters were determined through simulation, we further conducted test experiments on the training ground. The tether length is set to 300mm, the gripping angle is 20 degrees, and the loading pressure value is changed between 4.0 MPa and 4.5 MPa. The measured projection height and projection distance are shown in Table 1.When the driving pressure is 4.5 MPa, the grip angle is 20 degrees, and the tether length is 300 mm, the initial angle of the throwing rod changes between -10 degrees and 20 degrees. The measured projection height and throwing distance are shown in Table 2.When the driving pressure is 4.5 MPa, the initial angle of the throwing rod is 0 degrees, the length of the tether is 300 mm, and the gripping angle is changed between 15 degrees and 25 degrees. The measured projection height and throwing distance are shown in Table 3.

TABLE 1. Driving Pressure Test

Loading pressure /MPa	x/m	y/m
4.0	9.6	3.1
4.1	9.58	3.3
4.2	9.61	3.3
4.3	9.7	3.4
4.4	9.75	3.5
4.5	9.8	3.6

TABLE 2. Initial Angle of the Throwing Rod Test

Angle of proj. bar /Deg.	x/m	y/m
-10	8.6	2.8
0	9.8	3.6
10	10.6	3
20	12	2.7

TABLE 3. Gripping Angle Test

Gripping angle /Deg.	x/m	y/m
15	10	3.2
20	9.8	3.6
25	9.61	3.3

Combining simulation analysis and experimental tests, the best control parameters were determined as follows: initial projection angle of the projection rod 0 degrees, tether length 300mm, driving air pressure 4.5 MPa, gripping angle 20 degrees. The above parameters meet the requirements for "Dragon Shuttlecock" competition. In the official competition in China in June 2018, we successfully completed the competition task by operating the independently developed robots. In the end we won the national third prize.

V. Conclusions

The background of this article is the ABU Asia-Pacific Robot Contest in 2018, and the technical field involved is the throwing robot. This article gradually completed the design of the throwing mechanism from the aspects of theoretical analysis, simulation analysis and experimental testing. First of all, in the theoretical design part, the key design parameters were determined, the planning of the trajectory was achieved, and the foundation for the structural design of the throwing mechanism was laid. Then, combined with the design of the throwing mechanism, the rigid-flexible coupled multi-dynamics simulation analysis was performed. The rigid-flexible coupled multi-body dynamics simulation analysis provided intuitive details for optimizing the control parameters of the throwing mechanism and determined the optimal control parameters. Finally, actual test verification was carried out to determine the optimal control parameters and flight trajectories.

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