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Design and Testing of a Bungee Cord Based Launcher for LSU-02 UAV

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ABSTRACTS

The LSU-02 is one of the unmanned aerial vehicles (UAVs) developed by LAPAN (now BRIN). It has a good endurance and flight range, i.e., it can fly for four hours and up to 200 km. However, the UAV needs a good and long runway to do the takeoff and landing operations. In real missions, sometimes it is hard to find the proper runway. Therefore, a method for taking-off without a runway, namely using a launcher, is required. The two most frequently used launcher systems are pneumatic launcher and bungee cord launcher. However, based on our experience using the launcher for LSU-03 UAV, a pneumatic launcher is considered less practical due to its complex and heavy construction. For the LSU-02 to be able to carry out missions in remote areas, a simpler and lightweight launcher is needed. Therefore the bungee cord-based launcher was chosen. The initial requirement for the launcher is that the launcher should able to push the LSU-02 with a maximum takeoff mass of 15 kg put on a 7 kg cradle (total mass 22 kg) and reach the launch speed of 15.2 m/s at the end of launching track. The simulation result shows that the launcher needs a time of 0.28 s to achieve a velocity of 15.2 m/s. Meanwhile, in 0.28 s, the UAV travel distance is 2.55 m. This is the minimum effective length required by the launcher. The real launcher was built with an effective length of 2.7 m. The launcher was tested for launching the LSU-02 with the UAV takeoff mass of 14.4 kg and the cradle mass of 7.5 kg (total of 21.9 kg). It was able to successfully launch the LSU-02 in 0.27 s with a travel distance on the launching rail of 2.5 m.

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INTRODUCTION

LAPAN (now BRIN) has several types of unmanned aerial vehicles, which are referred to as LAPAN surveillance UAV (LSU). The LSUs can be utilized for many applications, such as aerial photography for agriculture, mapping, and disaster management, as well as for maritime surveillance [1]-[3]. For the use of disaster management, for example, LSUs have the ability to take pictures of volcanoes. LSU-01 has experience in taking pictures of the Merapi volcano, but it has a limitation on the flight range and endurance. When a volcano is on alert status, people are prohibited to approach the volcano at a certain distance. Therefore we need to develop UAVs with a longer endurance and flight range. The LSU-02 is a UAV that can fly for up to four hours with a range of up to 200 km. Furthermore, if a UAV is needed that can fly even further, we have the LSU-03, which has the ability to fly up to 340 km. However, this UAV is heavy (30 kg) to

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be carried mobile and needs a longer runway, so the LSU-02 is preferred.

The LSU-02 needs a proper runway to be able to take off and land successfully. However, in many missions, such as in mountain, forest, and maritime surveillance, it is hard to find a long and good runway that can be used for the LSU-02 takeoff and landing. A lightweight launching and landing system will be very useful for the LSU-02 in such missions, so a launcher and a parachute recovery system are needed. This paper will focus on the design of a launcher for LSU-02, as well as its testing.

LAUNCHER DESIGN

Launcher Design Theory

The design of a launcher system must consider the number of personnel needed to operate, must be lightweight, has compact storage, and can be reassembled as quickly as possible to launch the UAV. The number of operator reflects the practicality of the launcher and the personnel costs. A lightweight and small launcher are needed, especially for use on ships and other small areas. Besides, it also simplifies and speeds up launcher mobility. Compact storage will also facilitate mobility to remote and hard-to-reach areas. Furthermore, the easiness and speed of assembling the launcher are also needed for military purposes and disaster management. In addition, easy maintenance is also required. The availability of spare parts (easily and quickly) is very helpful in maintenance. When the UAV is on the launcher, a system that is safe, reliable, and easy to operate is required. A safe system is needed so that the UAV will never be suddenly ejected and endanger the operators. For this reason, there is a need for safety systems and SOP. Besides, the system and its components must be reliable, considering the difficulty of getting spare parts in the operating area. The easiness of operation is also important to reduce human error.

There are five launching device systems (LD) commonly used for launching UAVs: pneumatic, hydraulic, bungee cord, kinetic energy and rocket assisted take off (RATO) systems [4]-[8]. Also, there are other systems, such as electromagnetic LD [9] and spring drive LD [10]. Among those, the pneumatic and bungee cord LDs are the most frequently used. Pneumatic LD can produce more power and is suitable for launching bigger UAVs. However, based on our experience of designing and operating the launcher for LSU-03 UAV, the use of a launcher with a pneumatic system is considered less practical. In addition to requiring a sturdy and heavy construction, we must also bring a tube filled with high-pressure air. Therefore, for the LSU-02, it is necessary to design another launching device that is simpler and lighter. Considering the easy-to-use scenario, a bungee cord launcher was chosen.

The initial design requirement for the bungee cord launcher is tailored to the UAV that will be launched. The design requirements of the launcher refer to the specification of the LSU-02 UAV. Besides, since a cradle will be used to hold the UAV, the launcher must be able to produce force to push both the UAV and the cradle altogether along the launcher rail. The LSU-02 maximum takeoff mass is 15 kg, and the required takeoff speed is 15.2 m/s. The cradle mass will be 7 kg. Hence the design requirements of the launcher for LSU-02 are as follow:

- The UAV + cradle maximum mass: 22 kg
- The launch speed: 15.2 m/s

Bungee Cord-based Launcher Design

The main parts of a bungee cord launcher are the launching rail (the main part of the launcher where the UAV launches), the cradle (where the UAV slides to the end of the launcher), the elastic bungee cord set (for pulling the cradle), roller (for bungee cord support), and retainer (for retaining the cord). We based our launcher design on the design described in Ref. [4] with minor modifications, i.e., we use only one roller instead of two rollers (front and end).

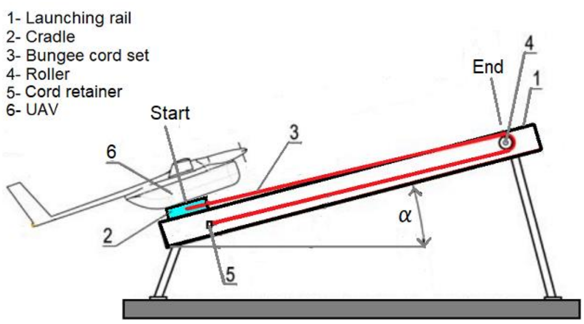

Figure 1. The design of the launcher (based on [4]).

The bungee cord is tied one end to the retainer and the other end to the cradle. The bungee cord will experience maximum tension when the cradle is pulled and tied at the start position. When the cradle strap is released, the cradle, altogether with the UAV, will slide along the launcher. The cradle will stop at the end of the launcher, and the UAV will be released and will then fly with the thrust from its propellers. The distance from the Start to End position is the launcher effective length. The position of the retainer can be set back and forth to adjust the tension of the bungee cord. The tension is adjusted according to the UAV + cradle mass.

The UAV slides along the launcher rail with the help of forces from the bungee cord tension and the thrust of the UAV engine. The speed of the UAV when reaching the end of the launcher, i.e., the launch speed, must meet the UAV takeoff speed.

Mathematical Model

The forces that work on the launcher are as shown in **Figure 2**. Mathematical model of the launcher system can be expressed as follows [4].

$$m\vec{a} = \vec{F_e} + m\vec{g} + \vec{F_\mu} + \vec{R_x} + \vec{R_z} + \vec{T} + \vec{N} \quad (1)$$

Where m is the mass of the UAV and cradle, a is acceleration, F_e is the force of the bungee cord, g is the gravitational force, F_μ is frictional sliding force, R_z is UAV lift force, R_x is the drag force, T is UAV propulsive force, and N is the normal force.

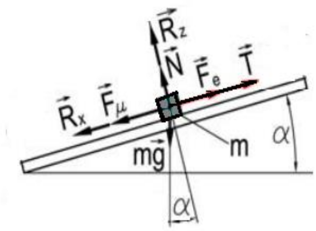

Figure 2. Forces working on the launcher.

Reference [4] assumes and has numerically shown that the UAV drag force and lift force can be neglected because their values are very small. Other assumptions are used to simplify the model, as follows.

- The mass of the bungee cord and the roller are neglected because they are small compared to the mass of the UAV and the cradle.
- The direction of forces of the bungee cord and the UAV thrust are coplanar to the launcher plane.
- The friction force of the bungee cord and the roller is neglected.
- The stiffness of the bungee cord is constant.
- The bungee cord pulling force is linear to its elongation.
- The UAV propulsive force is constant.

Reference [4] provides a solution of the mathematical model to calculate the UAV travel distance, velocity, and acceleration on the launcher as follows.

$$x(t) = \left[x_0 + \frac{T+n_r}{q_r} - \frac{mg}{q_r}(\mu cos\alpha + sin\alpha) - b\right] cos\sqrt{\frac{q_r}{m}}t + \frac{mg}{q_r}(\mu cos\alpha + sin\alpha) + b - \frac{T+n_r}{q_r} \quad (2)$$

$$\dot{x}(t) = -\left[x_0 + \frac{T+n_r}{q_r} - \frac{mg}{q_r}(\mu cos\alpha + sin\alpha) - b\right] \sqrt{\frac{q_r}{m}} sin\sqrt{\frac{q_r}{m}}t \quad (3)$$

$$\ddot{x}(t) = -\left[x_0 + \frac{T+n_r}{q_r} - \frac{mg}{q_r}(\mu cos\alpha + sin\alpha) - b\right] \frac{q_r}{m} cos\sqrt{\frac{q_r}{m}}t \quad (4)$$

Where x_0 is bungee cord length, b is bungee cord length un-stretched, T is engine thrust, n_r is bungee cord offset, q_r is bungee cord stiffness, m is UAV+cradle mass, μ is kinetic friction coefficient, α is launching rail elevation angle, and t is time. The $x(t)$ is the length of the bungee cord with respect to time. The $\dot{x}(t)$ and $\ddot{x}(t)$ are the velocity and acceleration of the UAV on the launcher with respect to time, respectively.

The UAV travel distance d is obtained as follows. The distance is used to determine the launcher effective length.

$$d = x_0 - x(t) \quad (5)$$

Bungee Cord Stiffness Measurement

The stiffness of the bungee cord is measured based on the initial length of the bungee cord, and then it is pulled with various length increments. The force per unit length of increment is measured as the stiffness of the bungee cord (N/m). The result of the measurement is shown in **Figure 3**.

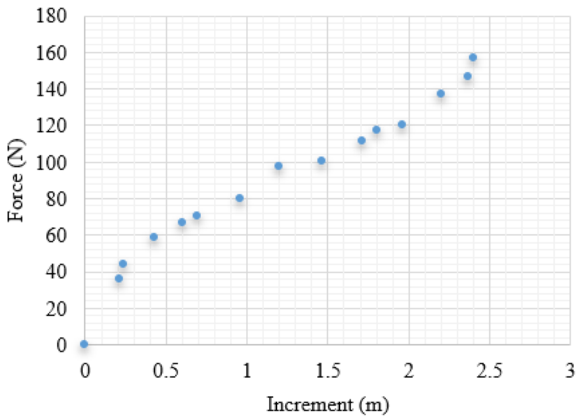

Figure 3. Bungee cord stiffness measurement.

Bungee cords usually have linear stiffness when they are stretched 20% to 80% of their original length, although this characteristic depends on the quality of the bungee cords. In this test, the bungee cord has a length of 2.4 m without tension, so the 20% and 80% increments in length are 0.48 m and 1.92 m, respectively. From **Figure 3**, it can be seen that the first and last data show non-linearity. If the first and last data are omitted, we have a linear regression (**Figure 4**) that represents the equation

$$y = 44.57x + 38.00 \quad (6)$$

Hence, for each bungee cord, we have stiffness q_r = 44.57 N/m and offset n_r = 38 N. With a total of 12 bungee cords used, we have q_r = 535 N/m and n_r = 456 N.

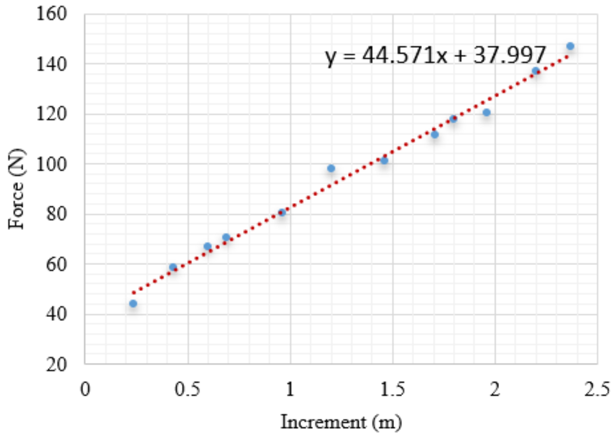

Figure 4. Bungee cord stiffness linear regression.

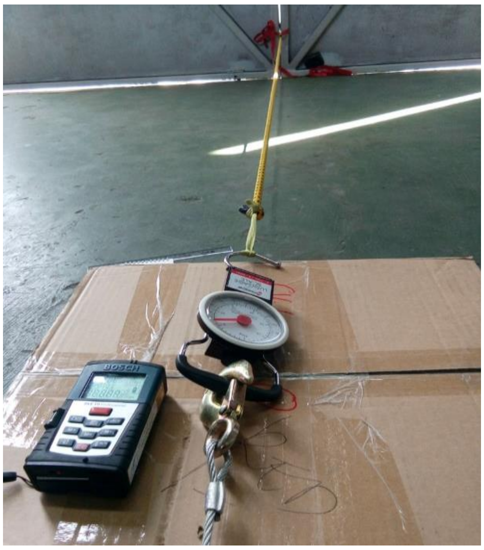

Figure 5. Measurement of bungee cord stiffness.

Simulation

Using equation (2)-(5), we can simulate the UAV acceleration, velocity, and travel distance on the launcher. The UAV and launcher parameters used in the simulation are summarized in **Table 1**.

The UAV acceleration, velocity, and travel distance are shown in **Figures 6, 7, and 8**, respectively. **Figure 6** shows the acceleration of the UAV on the launcher versus time. It can be seen that the bungee cord gives an acceleration of 7.6 G to the UAV at the start and then decreases. The acceleration will increase the UAV velocity over time (**Figure 7**).

Table 1. UAV and launcher parameters.

No.	Parameter	Symbol	Value	Unit
	- UAV maximum takeoff mass		15	kg
	- Cradle mass		7	kg
1	UAV+Cradle mass	m	22	kg
2	Bungee cord stiffness	q_r	535	N/m
3	Bungee cord offset	n_r	456	N
4	Bungee cord length	x_0	4.75	m
5	Bungee cord length un-stretched	b	2.4	m
6	Gravity acceleration	g	9.789	m/s^2
7	Launcher elevation angle	α	8	Deg
8	Kinetic friction coefficient	μ	0.096	-
9	Engine thrust	T	48.9	N

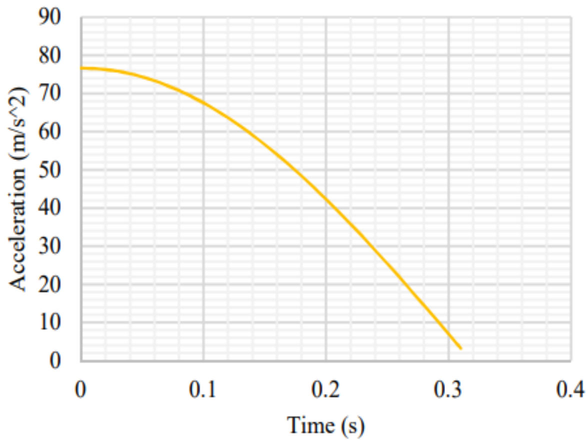

Figure 6. UAV acceleration vs. time.

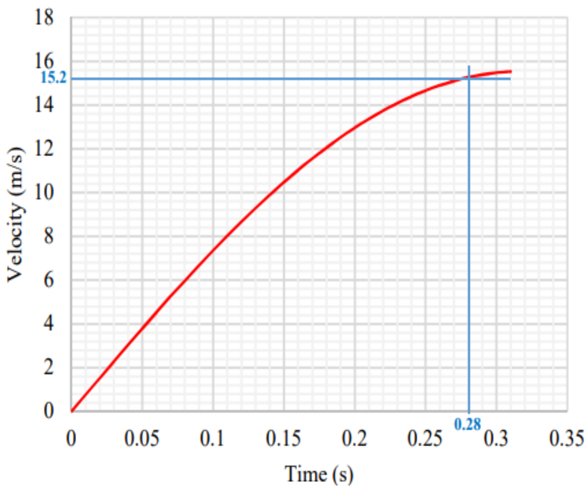

Figure 7. UAV velocity vs. time.

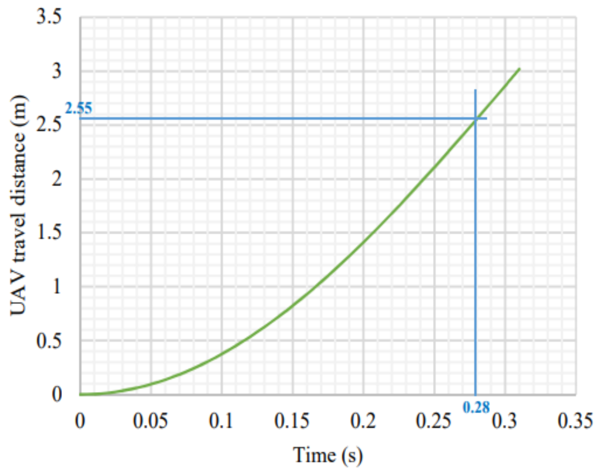

Figure 8. UAV travel distance vs. time.

From the requirement, the UAV velocity at the end of the launcher should be 15.2 m/s. It can be seen from **Figure 7** that the UAV needs 0.28 s to achieve that velocity. Meanwhile, in 0.28 s, the UAV travel distance is 2.55 m (see **Figure 8**). The travel distance is the minimum distance needed by the UAV to achieve the takeoff speed. Hence, the launcher should have a minimum effective length of 2.55 m to fulfill the requirement. The real launcher was built with an effective length of 2.7 m.

LAUNCHER TESTING

A lightweight launching and recovery system for LSU-02 will be very useful in remote areas where it is difficult to find a proper runway. The LSU-02 should be able to take off from the launcher and landing using a parachute. Here we conduct experiments to test the LSU-02 launcher.

We conducted a launching test with the UAV + cradle total mass was 21.9 kg. The cradle was 7.5 kg, a little heavier than the initial design (7 kg) due to structural strength considerations. With the increase in the cradle mass, the UAV mass was reduced by 0.5 kg to keep the UAV + cradle total mass not exceeding 22 kg. Hence the maximum UAV mass allowed was 14.5 kg. In our experiment, we gave a little spare and set the UAV mass to 14.4 kg, consisting of the UAV (12 kg), a dummy payload (1.6 kg), and 1 litre of fuel (0.8 kg).

It is worth mentioning that in an aerial photography mission, for example, a camera payload mass is typically about 0.6 kg. This means that in a real mission with only 0.6 kg payload (instead of 1.6 kg), the UAV can be filled with 1 kg (1.25 litre) more fuel. If the cradle mass can be reduced to 7 kg (while maintaining its strength), it will allow the UAV to bring more fuel and/or payload. In this experiment, however, our objective was not to test the UAV endurance nor to carry out the real mission. Instead, it was to test the launcher design, so the UAV was filled with a minimum fuel of 1 litre.

In the first test, there were some troubles we did not anticipate. Firstly, when the UAV was at the start position, it tilted up because the cradle was not rigidly attached to the launcher. Also, the cradle came off when it reached the end position of the launcher.

In the following tests, we ensured that the UAV was positioned properly and the cradle would not come off. We have made improvements to several sub-systems. Firstly, we repaired the uneven launcher rail joints. We also installed a cradle stopper made of rubber (see **Figure 10**) to prevent the cradle from coming off of the launcher. And we strengthened the roller so that it would not bend.

The UAV was put on the cradle, and the engine was turned on with idle throttle. When the bungee cord was released, it could launch out of the launcher properly. However, when the pilot increased the throttle, the throttle change was too sudden and generated a torque that caused the UAV to tilt to the left and then fell to the ground. **Fig. 11** shows the UAV exited from the launcher and crashed.

The next test was carried out with the UAV engine was set on a higher idle throttle to avoid such sudden throttle changes. The UAV successfully exited the launcher and was able to fly well (see **Figure 12**).

Figure 9. Launcher testing.

Figure 10. Cradle stopper.

Figure 11. LSU-02 exited from the launcher and crashed.

Figure 12. LSU-02 exited from the launcher and flew.

In order to validate our launcher design, we used a high-speed camera Casio EX-F1 to get the exact time when the UAV started to lift off from the launcher. The camera recorded a high-speed video of 300 fps. From the video footage in **Figure 13**, we get the time of the UAV start to lift off is 0.27 s from the start of the launching process, and it needs 2.5 m of travel distance on the launcher. On the other hand, the flight data logger did not record the flight data properly due to a technical problem, so we could not validate the UAV takeoff speed. However, with the successful launching of the UAV, we can conclude that the launcher is capable of meeting the requirement, i.e., to enable the UAV to achieve its minimum takeoff speed.

In the next experiments, a more robust flight data logging system should be installed. Besides, the cradle mass should be reduced to 7 kg while maintaining its strength to allow the UAV to its maximum takeoff mass (with payload and fuel) of 15 kg.

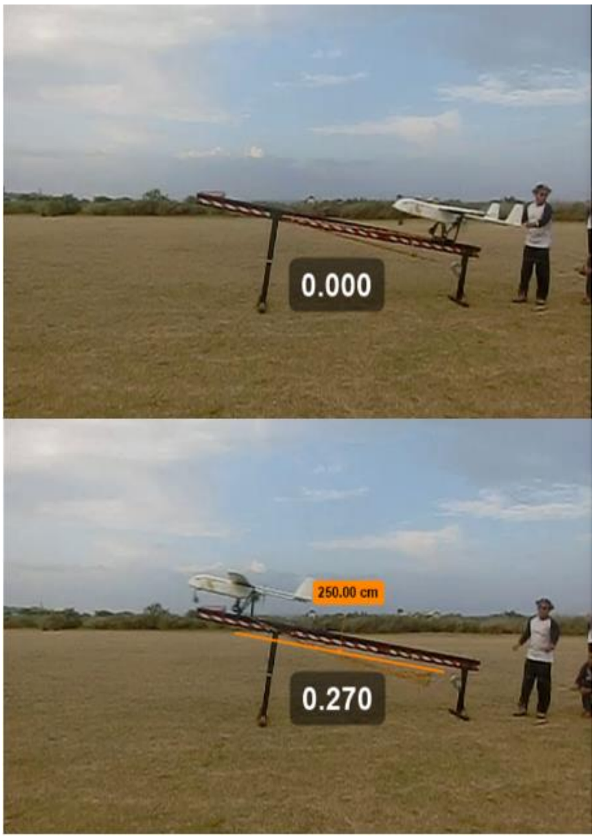

Figure 13. A clip from high-speed camera footage.

CONCLUSION

The design of a bungee cord-based launcher for the LSU-02 UAV has been carried out successfully. The initial requirement for the launcher is to be able to launch the UAV with a total mass of the UAV and cradle of 22 kg and reach the launch speed of 15.2 m/s at the end of the launcher track. The simulation result shows that the launcher needs a time of 0.28 s to achieve a velocity of 15.2 m/s. Meanwhile, in 0.28 s, the UAV travel distance is 2.55 m. The real launcher was built with an effective length of 2.7 m. The launcher was tested for launching the LSU-02 with the UAV takeoff mass of 14.4 kg and the cradle mass of 7.5 kg (total of 21.9 kg). It was able to successfully launch the LSU-02 in 0.27 s with a travel distance of 2.5 m on the launching rail.

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