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Towards Design of a Deformable Propeller for Drone Safety

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Abstract— **Drones have brought many benefits to our lives and their use is growing at a rapid rate. Many countries have drone flight restriction rules; however, the safety of drone operators and bystanders, and the protection of drones against damage require improvement. Here, we propose a novel design of deformable propellers inspired by dragonfly wings. The structure of these propellers includes a flexible segment similar to the nodus on a dragonfly wing. This flexible segment can bend, twist and even fold upon collision, absorbing force upon impact and protecting the propeller from damage. Part of the leading edge of the propeller consists of a pliable silicone rubber surface able to absorb impact forces and reducing blade sharpness. The propeller, which is approximately 10 inches long, can generate a thrust force of nearly 1.3 N at maximum velocity of about 3200 rpm. Results of blade sharpness tests showed that the deformable propeller was safer than a rigid propeller. After deformation upon collision, the propeller can return to its original form and work normally within 0.4 seconds.**

I. INTRODUCTION

Due to their versatility and low cost performance, drones are used in a variety of situations including shipping and delivery, search and rescue, disaster management, and entertainment. The structure of a drone can be classified into three main groups: motors and propellers, frames, and control and navigation systems. Each structural group has been investigated to determine suitable structures and functions.

A novel spherical drone was developed to protect its inner components, allowing the drone to roll along obstacles [1]. The spherical structure enabled the drone to avoid damage to propellers in collisions at particular trajectories, as well as allowing the drone to take off and land in any orientation. The design, however, was bulky and did not prevent damage to propellers in collisions in all trajectories. Other researchers focused on developing a safety frame for micro unmanned aerial vehicles (UAVs), with the ability to withstand high vibrations generated by the motor system, landing activities and external forces [2]. Some of these efforts focused on dual-axis tilting quadcopters, which use two servo motors on each arm of the drone to change its dimensions. This structure permits the drone to pass through a narrow space. Drone frame/structure strongly affects drone stability, as well as the ability to perform aerial tasks. Modification of drone structure is therefore required for drones to fulfill some certain requirements and tasks, such as safety and passage through a narrow area.

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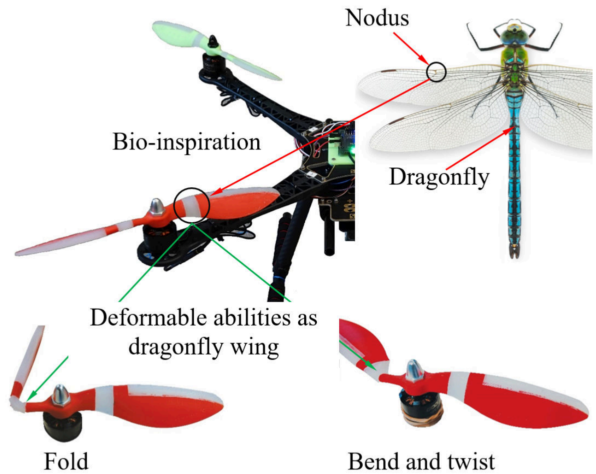


Fig. 1. Image of a safety drone, using a deformable propeller inspired by the nodus of a dragonfly's wing. The nodus can bend upon collision to protect the wing. The deformable trailing edge can partly absorb the force of impact and reduce the sharpness of the propeller.

Control issues related to drone functions have received more attention than issues related to drone structure. Visual sensors have been utilized for autonomous navigation and tracking ([3], [4]), as well as to track moving targets to avoid collisions ([5], [6]). These sensors have also been used in combination with smart phones to control drone movements while avoiding collisions [7].

The present study describes the development of a deformable propeller inspired by dragonfly wings (see Fig.1). A bendable segment constructed of silicone rubber and a nylon monofilament can partly absorb impact forces during collisions. Thrust force will be measured to determine the ability of the propeller to perform aerial tasks. Other important properties, including safety and self-recovery, will also be investigated.

II. RELATED WORKS

In recent years, many drone applications require drones to interact or work closely with humans or other objects. The safety of humans working in these conditions is jeopardized by the hardness and sharpness of propellers that rotate at high speed, ranging from several thousand to over ten thousand revolutions per minute (rpm). Risks may be due to the propellers and to pieces of broken propellers after collisions. Many researchers have investigated methods to enhance the safety of drones and minimize damage to surrounding areas.

A. Mechanical-related safety

During work with drones, humans are injured and objects damaged by direct contact with propellers. The first step in propeller design is a propeller protector that prevents such contact. However, a propeller protector cannot avoid collisions from all directions. For example, propellers remain dangerous if objects approach them vertically. Moreover, protection is bulky and heavy, which can reduce overall drone flight time. Alternatively, propellers can be made of softer material. Jang *et.al* [8] For example, a flexible blade can be made of a $100\,\mu m$ thick polyethylene terephthalate (PET) plate [8]. This propeller can easily bend upon collision, forming its original shape soon afterwards. When operated at high speed, however, this thin blade remains dangerous for soft obstacles, including human skin, if the contact region is at the tip of the propeller, which is rather sharp. Furthermore, larger-sized thin blades show greater deformation during rotation, limiting the use of these propellers for large UAVs.

B. Perception-based safety

Cameras have been used as visual solutions in control systems to avoid collision. For example, a collision avoidance system using stereo vision has been used to prevent the quadrotor of a drone from colliding with obstacles [9]. In addition, a linear model predictive controller (MPC), which combines states of virtual UAV obtained by a camera and a new avoidance algorithm to create control commands, has been proposed as a novel solution to avoid collisions [10]. However, due to the camera's sampling rate and visual occlusion, this MPC may not provide a complete solution for avoiding collisions.

C. Contributions

The present study describes the development of a novel hybrid propeller that deforms during collisions, then quickly resumes its original shape and works normally. This property assures that drones are safe for the surrounding environment if contact occurs. Fig. 1 shows this drone with a deformable propeller that contains a bendable segment inspired by the nodus of a dragonfly wing's. The generated thrust force and safety properties of this propeller were investigated. Contributions to this research are as follows:

1) Proposed the design of the novel deformable propeller inspired by the structure of a dragonfly wing.
2) Developed the deformable propeller, including the fabrication process. The propeller was found to generate an appreciable thrust force of around 1.3 N at its highest velocity of nearly 3200 rpm. The propeller was also found to be safer than a rigid propeller.

III. NOVEL DESIGN OF A DEFORMABLE PROPELLER

Because of potential applications that require direct interactions with or work near humans, safe drones have received considerable attention. One approach may be to use safe propellers. The structure of a dragonfly wing suggested the idea of a deformable propeller, which can bend, twist and even fold upon collision and resume its original shape soon afterward. This mitigates damage to the surrounding environment, including injury to humans, and avoids the risks of a broken propeller.

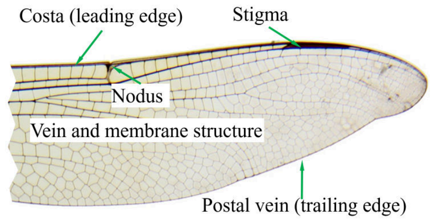


Fig. 2. Structure of the wing of a dragonfly (modified from [14]). The costa, postal vein, stigma and membranes are suitable for a flapping wing, whereas the nodus acts as a shock absorber, with wing deformation employed to construct rotating propellers.

A. Nodus of a dragonfly wing

The wing of a dragonfly, made of veins and membranes, is thought to enhance the aerodynamic performance of a dragonfly [14]. Fig. 2 shows the structure of a dragonfly wing, which is light in weight and suitable for flapping (dragonflies flap their wings at a rate of approximately 40 Hz). Stigma also increases the efficiency of wing stroke. The nodus of the wing, which has the structure of a one-way hinge can confer flexibility, as it permits the wing to twist and acts as a shock absorber [11], [12]. A nodus with a special mechanism and made of material called resilin, which is similar to isotropic rubber [13], can provide both structural reinforcement and shock absorption. The nodus enables a dragonfly wing to bend in both dorsal and ventral directions. A discontinuous structure with deformable parts may be employed for propellers which operate by rotating (not flapping) at rates of around 50 Hz to around 200 Hz.

B. Deformable propeller design

Propellers play the most important role for drone. The rotation of propellers creates the thrust force required for a drone's aerial activities. At high speed rotation, air flow exerts an appreciable force on the propeller blade, causing its deformation. Thus, a deformable propeller should have sufficient rigidity to retain its shape and pitch angle (θ in Fig. 5(b)), which strongly affect the generation of thrust force. Fig. 3 shows the design of a deformable propeller inspired by the nodus of a dragonfly wing. The deformable propeller is constructed from two main types of material, rigid and soft parts. The propeller hub, which contains the shaft of the motor and transfers torque from the motor, should be as rigid as possible. Therefore, the hub was composed of rigid plastic. Because the propeller was required to be tough enough, the wing was also made of rigid plastic. To mimic the properties of the nodus of a dragonfly wing, the soft parts of the deformable propeller were made of silicone rubber and nylon monofilaments. The rigid hub and rigid wings were connected by tendons made of nylon monofilaments. In addition, the stiffness of the propeller could be varied by changing the number of tendons. In

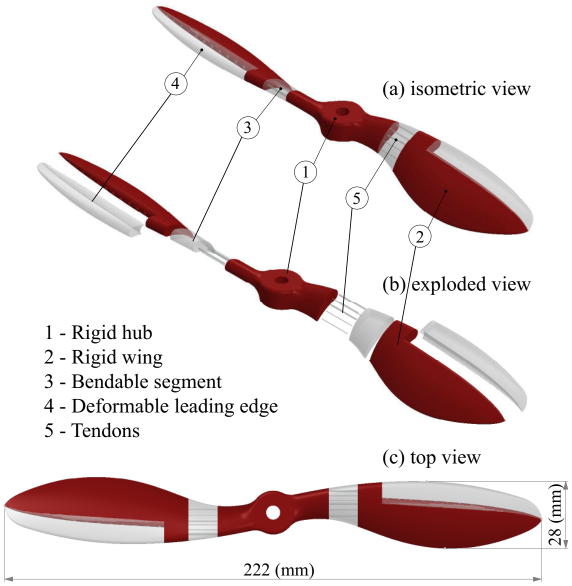


Fig. 3. Design of a deformable propeller. The propeller structure can be divided into two main groups: rigid parts responsible for the configuration the blade and soft parts to enhance safety.

this design, six tendons were used, a number that allows the proposed propeller to deform easily but also provides sufficient stiffness and toughness. The bendable segment was constructed from tendons and silicone rubber, which covers the tendons, to form a suitably shaped propeller. Similar to the nodus of a dragonfly wing, This segment can bend, twist, and fold when the propeller collides with another object. This flexion protects the propeller and reduces the impact force on the surroundings. A softened, deformable leading edge can partly absorb impact forces during collisions.

C. Deformable propeller fabrication

The rigid parts of the propeller were made of acrylonitrile butadiene styrene (ABS) plastic, the soft parts of silicone rubber Dragon Skin 20 (Smooth-On, Inc., USA) and the tendons of nylon monofilaments (2 filaments of diameter 0.85 mm and four of diameter 0.37 mm). Fig. 4 shows the seven-step fabrication process required to form a complete deformable propeller. (1) In the first step, the rigid parts and molds of the propeller were designed using SolidWorks. (2) In the second step, these rigid parts were printed using a 3D printer (M200 for the rigid parts and M300 for the mold parts, which are oversized when printed with the M200 printer Zortrax). (3) The tendons were affixed to the rigid parts using strong adhesive glue (PPX, Japan) to form the frame of the propeller. (4) This frame was placed onto the printed mold and (5) silicone rubber was poured into the mode to form a complete deformable propeller. (6) The propeller was released from the mold. (7) Finally, PPX glue was again used for strong adhesion between the soft and rigid parts. The process is utilized not only for the design shown in Fig. 3 but also for smaller sized propellers, including those 3 and 4 inches in size.

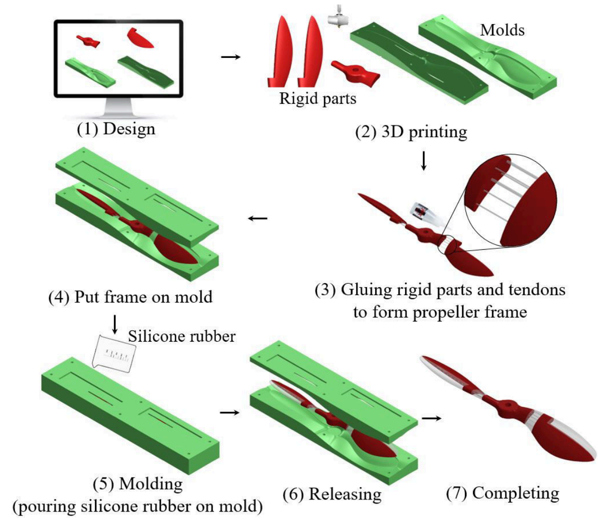


Fig. 4. Process for fabrication of the deformable propeller.

IV. AERODYNAMIC FORCES

The aerodynamic model shows the forces exerted by and on a rotating propeller. This model will be used to explain the variations in thrust force at different velocities and the differences in generated thrust forces between rigid and deformable propellers. Propellers rotating at a suitable velocity interact with the surrounding air to generate sufficient thrust force to lift the drone.

A. Generated thrust force by rigid propeller

Fig. 5 shows the exerted forces at an infinitesimal element along a propeller rotating at velocity v_2, also called inflow or out-of-plane velocity. Lift force can be calculated as [15]:

$$dL = \frac{1}{2}\rho C_L dA v^2, \tag{1}$$

$$dD = \frac{1}{2}\rho C_D dA v^2, \tag{2}$$

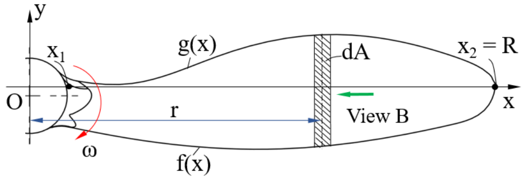
where ρ is air density, C_L and C_D are coefficients of lift force and drag force, respectively, dA is the area of the analyzed element, $\boldsymbol{v}$ ($v = |\boldsymbol{v}|$) is the total velocity vector of $\boldsymbol{v_1}$ and $\boldsymbol{v_2}$ ($v_2 = \omega r$) are the out-of-plane and in-plane velocities, respectively. Thrust force at each propeller element dA can be expressed as [15]

$$\begin{aligned} dT &= dLcos\varphi - dDsin\varphi = \frac{1}{2}\rho dA v^2 (C_L cos\varphi - C_D sin\varphi) \\ &= \frac{1}{2}\rho[g(x) - f(x)]dx\omega^2 x^2 (C_L cos\varphi - C_D sin\varphi), \end{aligned} \tag{3}$$

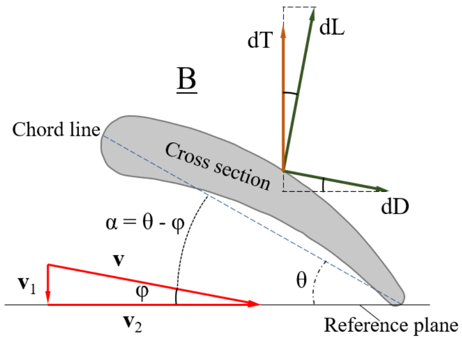
where φ is the angle between $\boldsymbol{v}$ and $\boldsymbol{v_1}$, and ω is the angular velocity of the propeller ($\omega = 2\pi n$, where n is rotation speed, expressed as rpm).

Total thrust created by both halves of the propeller can be calculated as:

$$\begin{aligned} T = 2\int_{x_1}^{x_2} dT = \\ \int_{x_1}^{x_2} 4\rho\pi^2 n^2 (C_L cos\varphi - C_D sin\varphi) x^2 [g(x) - f(x)]dx, \end{aligned} \tag{4}$$



(a) Top view of a half of designed propeller



(b) Cross section view at element dA

Fig. 5. Forces exerted on an element of the propeller.

where x_1 and x_2 are radius of innermost and outermost curvatures, respectively, that are boundaries of the propeller's thrust-force generation part. $f(x)$ and $g(x)$ are geometric functions of the leading and trailing edges, respectively. These functions depend on the design of the propeller (see Fig. 5(a)), with v_2 being much larger than v_1. Therefore, to simply calculations, it was assumed that $|v| = |v_2|$, i.e. $\varphi \to 0$. Thus, the attack angle α was equal to the pitch angle θ (see Fig. 5(b)). In this case, total thrust forces can be expressed as:

$$
\begin{aligned}
T &= \int_{x_1}^{R} 4\rho\pi^2 n^2 C_L x^2 [g(x) - f(x)]dx \\
&= \int_{x_1}^{R} 4\rho\pi^2 n^2 [0.225 + 1.58 sin(2.13\theta - 7.2)] x^2 [g(x) - f(x)]dx \\
&= 4\rho\pi^2 n^2 \int_{x_1}^{R} F(\theta_x, x)dx.
\end{aligned}
\tag{5}
$$

Eq. (5) indicates that the generated thrust force depends on two main parameters, propeller rotation speed n and propeller pitch angle θ. The effect of pitch angle on thrust is determined by $C_L = 0.225 + 1.58 sin(2.13\theta - 7.2)$ [16]. In our design, θ is less than 40 deg. In this range, a reduction in pitch angle results in a reduction of C_L, thereby decreasing thrust force. Similarly, an incremental increase in rotation speed results in an increase in thrust force. Furthermore, because thrust generated thrust force is affected by the square of rotation speed and by the sine of the pitch angle, rotation speed has a much greater effect than pitch angle on generated thrust force.

B. Generated thrust force by deformable propeller

In contrast to rigid propellers, the proposed propeller deforms during rotation, resulting in variations in generated thrust force. This section constitutes a preliminary analysis of the variation in thrust force generated by the deformable propeller. Fig. 6 shows the alterations during rotation of the pitch angle θ_d of a deformable propeller, resulting in changes in generated thrust force (5). Because of the structure of the propeller, the force exerted on the part of the propeller near the trailing edge (orange curve in Fig. 6) is larger than the force exerted on the part near the leading edge. This results in deformation, thereby reducing the pitch angle. A 0 to 40 degree reduction in θ will lead to a decrease in thrust force. The thrust force generated by a deformable propeller may therefore be lower than the thrust force generated by a rigid propeller. Because a higher speed causes greater deformation, a higher speed may result in a greater difference between thrust forces generated by rigid and deformable propellers.

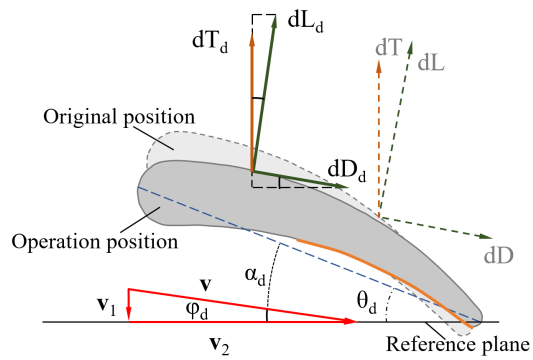


Fig. 6. Deformation of the proposed propeller at high rotational velocity, reducing the pitch angle and leading to a change in thrust force.

V. PROPERTIES OF THE DEFORMABLE PROPELLER

Three main properties of the deformable propeller were analyzed, ability to generate thrust force, safety, and ability to recover shape after collisions.

A. Generation thrust force

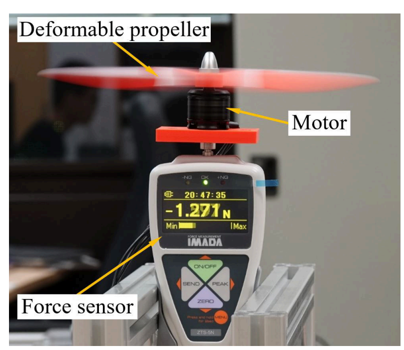


Fig. 7. Device for measuring the thrust force on the deformable propeller.

Fig. 7 shows the experimental setup for measuring thrust force. The setup used a ZTS-5N force gauge (IMADA-Japan) with a resolution of 1 mN, and a X2212 960KV motor. The thrust forces generated by rigid and deformable propellers of the same size were measured at various rotation speeds (8). At the same rotation velocity, the thrust force

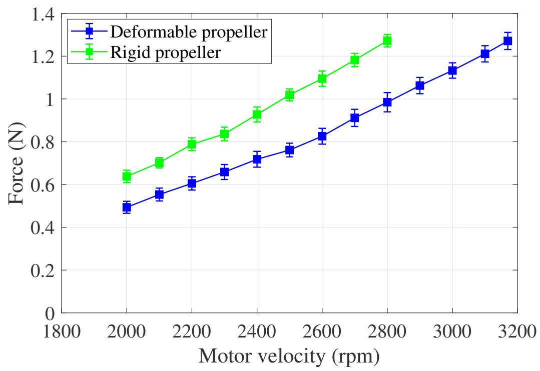
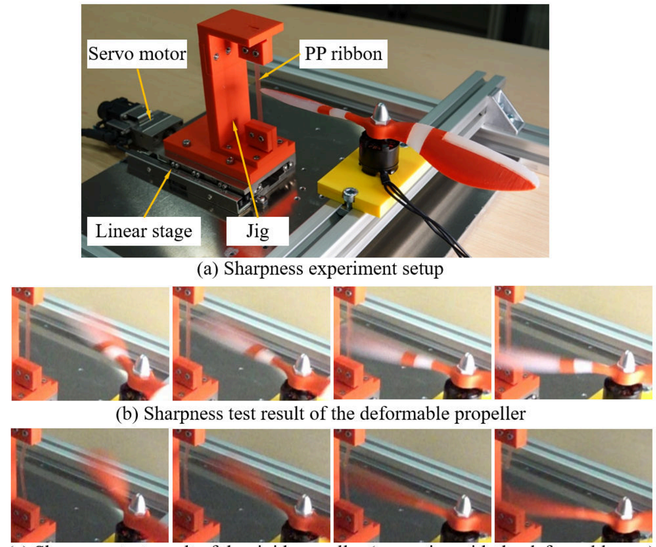


Fig. 8. Thrust forces generated by a rigid and a deformable propeller. The thrust force generated by the deformable propeller was approximately 22.6 % lower than the thrust force generated by the rigid propeller at the same rotation speed. The maximum rotation speeds of the motor with the rigid propeller was 2800 rpm, whereas the maximum speed with the deformable propeller was 3200 rpm.



(a) Sharpness experiment setup

(b) Sharpness test result of the deformable propeller

(c) Sharpness test result of the rigid propeller (same size with the deformable one)

Fig. 9. Cutting test to assess the safety of the deformable propeller. (a) Experimental setup, (b) Test of sharpness of the deformable propeller. (c) Test of sharpness of the rigid propeller.

generated by the deformable propeller was slightly lower than that generated by the rigid propeller. The maximum velocities attained by the rigid and deformable propellers were 2800 rpm and 3200 rpm, respectively. The greater maximum velocity of the deformable propeller results in greater deformation at high speed and a decrease in pitch angle. Thus, at the same velocity, the drag force exerted on the soft propeller is smaller than the drag force exerted on the rigid propeller. At their highest speeds, the thrust forces generated by both propellers are roughly equivalent (just under 1.3 N). In general, at similar operating conditions, the difference between the thrust forces generated by the deformable and rigid propellers is small.

B. Safety properties of the deformable propeller

1) Sharpness test: The ability of a deformable propeller to replace a rigid propeller is dependent on the ability of the former to reduce risks to humans and other objects during collision. The sharpness of these propellers was therefore compared. Obstacles consisted of polypropylene ribbons, measuring 4x0.2 mm in width and thickness, respectively. The obstacles were held in a stretched situation by a jig, which was fixed onto a linear stage operated by a servo motor (X-Axis linear ball guide PG650 - Segura Seiki - Japan) at maximum velocities of 2800 rpm for the rigid propeller and 3200 rpm for the deformable propeller. The obstacles were slowly moved toward the rotating propeller until they collided. Data were recorded at 960 fps using a Sony DSC-RX10M4 camera and analyzed by Matlab R2019a software.

Fig. 9 shows the images obtained from slow motion videos of the cutting tests of the rigid and deformable propellers. The polypropylene ribbon was cut by the rigid propeller, but not by the deformable propeller, upon collision, indicating that the soft parts enhance the safety of the deformable propeller. The lack of cutting by the deformable propeller may be due to the deformation of the soft edge and the deformable segment (bending and twisting), reducing the force of impact and the sharpness at the tip of the deformable propeller.

2) Collision test: Another risk comes from pieces of a broken propeller moving at high speed. Rigid propellers are easily broken after collisions and the broken pieces of the propeller are dangerous for nearby humans and other objects. Therefore, for safety purposes, propeller should not break after collision. Collision tests were therefore performed to investigate the stability and toughness of the deformable propeller. Fig. 10 shows the setup and results of these tests. The deformable propeller was operated at its highest speed (approximately 3200 rpm). A model of a human finger made of silicone rubber (Dragon Skin 30) with a nylon monofilament core (to increase stiffness) was moved from the top to collided with the leading age of the propeller. Data were recorded at 960 fps using the Sony DSC-RX10M4 camera and analyzed using Matlab. The images the large deformation of the bendable segment upon collision. The three types of deformation observed, bending, twisting and folding, partly absorbed the impact force, reducing the forces exerted on both the finger model and the propeller. Furthermore, the deformability made the propeller tougher because it partly absorbed the impact force. Thus, the propeller was more stable and more difficult to break upon collision. Moreover, the deformable propeller was able to self-recover and work normally within 0.4 sec after collision.

VI. DISCUSSION

The results of thrust force measurements indicated that, at the same velocity, the thrust force generated by the deformable propeller was moderately lower (approximately 22.6 %) than that generated by the rigid propeller, with the increases corresponding to the increase in motor velocity. This phenomenon is caused by the deformation of the

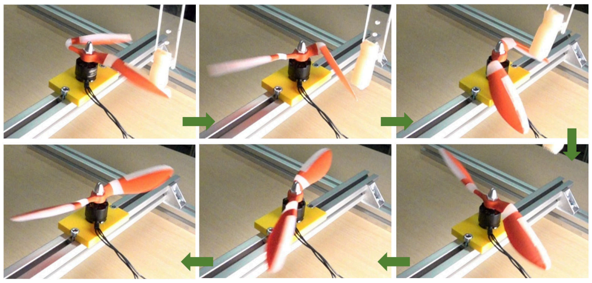


Fig. 10. Test of collision of the deformable propeller at a rotation speed of 3200 rpm. The propeller self-recovered and worked normally within 0.4 sec.

deformable propeller. The differences depend on the velocity of the motor and the deformability of the soft parts of the propeller, which can be varied by constructing the soft parts of the propeller from different types of silicone rubber and/or by altering the number of tendons. Generated thrust force is the most important property of a propeller, as it represents the ability of drones to perform aerial tasks. Prediction of thrust forces contributes to a suitable design, which optimizes time and fabrication costs. This requires construction of a model deformable propeller of the testing of aerodynamic forces exerted by rotation. This model can test the effects of soft materials, the structure of the soft part and rotation speed on generated thrust force. This model can also test the intensity of vibrations due to the "soft" specifications of the propeller, because this phenomenon strongly affects the stability of drones during aerial tasks.

Evaluation of safety showed that the soft parts of the deformable propeller could partly absorb impact forces during collisions. In addition, a bendable segment with tough tendons was found to enhance the toughness of the propeller, which may protect the propeller from breaking upon collision with its surroundings. The ability of the propeller to absorb impact forces and generate thrust forces depends on the specifications of the soft materials used to construct the soft parts of the propeller. These issues will be investigated in future studies.

VII. CONCLUSION

This paper introduced a novel design of deformable propeller for safety purposes. The design was inspired by dragonfly wings, containing a bendable segment that functions similar to the nodus of a dragonfly wing. This segment was able to bend, twist, and fold to partly absorb impact forces during collisions. Furthermore, this structure enhanced the toughness of the propeller, which may help it recover after colliding. The deformable propeller was able to generate appreciable thrust force. At its highest velocity 3200 rpm, it generated approximately 1.3 N of thrust force, similar to the thrust force of 1.2 mN generated by the rigid propeller operated at its highest speed of 2800 rpm. Safety testing also showed that the deformable propeller was safer than the rigid propeller. In addition, upon collision, the deformable propeller was able to self-recover and work normally within 0.4 seconds after collapsing.

In future work, we will build the thrust force model of a deformable propeller. This model may be able to predict the effects of soft part stiffness and operating velocity on thrust force. We will also test the effects of various types of soft materials utilized to construct soft parts of deformable propellers on drone safety and aerial abilities.

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