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A Feasibility Study of Lightweight Polylactic Acid Fused Deposition Modeled Propeller Prototyping

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ABSTRACT

From the inception of fused deposition modeled (FDM) 3D printing, various materials have been introduced as filaments. Lightweight polylactic acid (LW-PLA) has been introduced as a 3D printing material by a company named ColorFabb, and it has a unique property to expand at around 230°C. The expansion can be calculated and harnessed to create more lightweight 3D printed models. Previous studies have used ANSYS computer simulations to gauge the feasibility of 3D printed propellers of various materials. Previous studies that tested propellers in real life have shown that propellers made from polylactic acid (PLA), another 3D printing plastic, are only feasible for prototyping purposes. This study attempted to find feasibility of LW-PLA in the FDM prototyping of propellers by using a real life testing apparatus to compare LW-PLA and PLA propellers. 4 propeller designs were made, and PLA and LW-PLA counterparts were created for each design. A significant difference in thrust-efficiency ratio was found between LW-PLA and PLA propellers, indicating that LW-PLA propellers were not feasible for propeller prototyping. It was observed that the application of acrylic sealer coatings to both LW-PLA and PLA propellers decreased the difference, but the difference was still significant in most cases. Additionally, LW-PLA propellers were observed to be about 50% of the weight of their PLA counterparts, indicating that LW-PLA propellers may be useful in situations where weight is required to be minimized. This study is significant in that it addresses the major gap in the research of LW-PLA and its applications in aerospace.

Literature Review

Biobased Lightweight Polylactic Acid, or LW-PLA, is an experimental material invented by engineers from ColorFabb, a well-known manufacturer of quality filament for 3D printers.[1] Because of its experimental nature and the fact that it was just recently invented and introduced to consumers, there is little research on LW-PLA in an aerodynamics setting. This research attempts to discover the extent to which an LW-PLA propeller is feasible for usage in the fused deposition model (FDM) prototyping of propellers in terms of weight and thrust-efficiency ratio in order to increase access to an efficient lightweight propeller.

Lightweight Polylactic Acid (Expanding Polylactic Acid)

ColorFabb has released a 3D printing guide with an explanation of the physical properties of LW-PLA. When heated to temperatures around 230°C, LW-PLA begins to expand to create microscopic air bubbles from the surrounding atmosphere, giving it the synonymous title of Expanding Polylactic Acid, or E-PLA. FDM 3D printing involves the extrusion of plastic through a nozzle to “draw” several layers consisting of 2D slices of a

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[1] How to print with LW-PLA. (2019, April 11). *Learn ColorFabb.* https://learn.colorfabb.com/print-lw-pla/.

3D object. However, the expansion of LW-PLA causes an FDM 3D printer to become less accurate because there will be overlaps of plastic between layers as a result of a larger volume of plastic being extruded. The way to solve this problem is by decreasing the extrusion rate of LW-PLA, which allows less material mass to be released to create the same solid volume as compared to using PLA. Therefore, LW-PLA can cause a solid to be created with less than 50% of the material of the same solid made from PLA. Because of its weight reduction properties, LW-PLA is primarily used in the creation of RC aircraft, where minimal weight provides an optimal flight.

Current Research

While there has been little research on LW-PLA, there has been more research on topics corresponding to this area of interest, including propeller research and 3D printing research in general. This research attempts to address the gap in the aeronautical research of LW-PLA.

Computer Simulation

There has been little research on 3D printed propellers regardless of material. Most studies on 3D printed propellers use a version of ANSYS, a physics modeling software.[2] [3] ANSYS uses a surrogate model, which uses statistics to generate a margin of error for points on a plane, so every point on the plane does not have to be calculated and just a fraction of the points could be used to statistically "guess" the other points of the surface while maintaining a level of accuracy.[4] The surrogate model allows the generation of physics models for complex structures without the need for a supercomputer. While the studies that used ANSYS have certainly generated quality physics models of propellers, only one of them 3D printed a physical propeller (0.8mm layer height), which was not feasible for flight on the test drone (DJI Mavic Pro).[2] The physics models generated by ANSYS for 3D printed parts may not actually apply entirely to the real world due to factors such as layer height and layer lines (discussed in Methodology) that ANSYS does not address. Another reason ANSYS will not be used to model the propellers is that it can cost several thousand dollars to run a version of ANSYS that performs the physics calculations necessary for this project, which is not feasible.

<u>3D Printed PLA Propellers (Feasibility Standard):</u> One study did 3D print propellers made from PLA and attempted to find feasibility instead of using software like ANSYS.[5] This study concluded that PLA propellers printed with the same printing settings used in the study could be used to predict the performance of injection-molded propellers during the prototyping process. Their method included comparisons of thrust-efficiency. The researchers found that FDM PLA propellers are not feasible for mass production due to their low impact strength thanks to layer lines (Discussed in Methodology) similar to the limitations of ANSYS simulations for 3D printed

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[2] Krmela, J., Bakosova, A., Krmelova, V., & Sadjiep, S. (2021). Drone propeller blade material optimization using modern computational method. *20th International Scientific Conference Engineering for Rural Development Proceedings*. https://doi.org/10.22616/erdev.2021.20.tf199.

[3] Malim, A., Mourousias, N., Marinus, B. G., & De Troyer, T. (2021). *Aeroelastic response simulation of a 3d printed high altitude propeller* [Video Presentation]. AIAA AVIATION 2021 FORUM. https://doi.org/10.2514/6.2021-2490.

[4] Carroll, J., & Marcum, D. (n.d.). Local adaption capabilities of momentum source surrogate models for propeller-aircraft coupled situations. *Engineering Letters, 21*(4), 247-255. http://www.engineeringletters.com/issues_v21/issue_4/EL_21_4_11.pdf.

[5] Toleos, L. R., Andrew, N. J., Luna, D., Manuel, M. C. E., Chua, J. M. R., Sangalang, E. M. A., & So, P. C. (2020, April). Feasibility Study for Fused Deposition Modeling (FDM) 3D-Printed Propellers for Unmanned Aerial Vehicles. *International Journal of Mechanical Engineering and Robotics Research, 9*(4), 548-558. http://www.ijmerr.com/uploadfile/2020/0312/20200312030012755.pdf

propellers. However, Toleos Et. al did conclude that FDM PLA propellers are indeed feasible for the prototyping of injection-molded propellers. Because PLA propellers have been confirmed to be feasible for prototyping purposes in terms of thrust-efficiency ratio, an LW-PLA propeller of the same design as a PLA propeller could be used to find the feasibility of LW-PLA propellers for prototyping. If there is no statistically significant difference between the thrust efficiency ratio of LW-PLA propellers and PLA propellers of the same design, then it will be confirmed that LW-PLA propellers must also be feasible for prototyping.

Infill Structures

The primary issue that made PLA propellers unfeasible for mass production in Toleos Et. al.'s study was low impact strength. Proper usage of infill structures can make a solid considerably stronger. When 3D printing a solid, the outer surface is what matters to attain the purpose of that solid. On the inside, there can be various infill structures rather than making this structure solid plastic to save both weight and material, possibly even making the structure stronger. Most studies generally conclude that a cellular infill pattern, where the interior is separated into separate sectors or cells, is best for absorbing forces because force can travel between cells efficiently, whether rectilinear, honeycomb, or gyroid in cell shape.[6] [7] [8] However, among cellular infill patterns, the gyroid has the best ratio of tensile and flexural strength to weight.[6] The gyroid is found in nature in plant cell structure, and it can be described as a series of stacked circles. This study will be using 20% gyroid infill for all of the test models of the propellers (Figure 3).

Methodology

An experimental research method combined with comparative research was used. Four propeller designs were generated using Creo, an industry-standard computer-aided design (CAD) software, which also includes stress testing simulations, and they were 3D printed in both LW-PLA and PLA. These propellers are based on a 10" Windsor Propeller.[9] However, the central sections are larger in these designs, as 3D printed models may break along thin sections easily.[3] These propellers were printed using the settings used by Toleos Et. al.[5] LW-PLA variants used the same print settings, but at 235°C and 50% flow rate to account for expansion.

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[6] Khaderi, S. N., Deshpande, V. S., & Fleck, N. A. (2014). The stiffness and strength of the gyroid lattice. *International Journal of Solids and Structures, 51*(23), 3866–3877. https://doi.org/10.1016/j.ijsolstr.2014.06.024.

[7] Khan, S. F., Zakaria, H., Chong, Y. L., Saad, M. a. M., & Basaruddin, K. (2018). Effect of infill on tensile and flexural strength of 3D printed PLA parts. *IOP Conference Series: Materials Science and Engineering, 429*(1), 012101. https://doi.org/10.1088/1757-899X/429/1/012101.

[8] Lubombo, C., & Huneault, M. A. (2018). Effect of infill patterns on the mechanical performance of lightweight 3D-printed cellular PLA parts. *Materials Today Communications, 17*, 214–228. https://doi.org/10.1016/j.mtcomm.2018.09.017.

[9] *GF Series—10x6 Propeller.* (n.d.). Master Airscrew. Retrieved December 9, 2021, from https://www.masterairscrew.com/products/gf-series-10x6-propeller

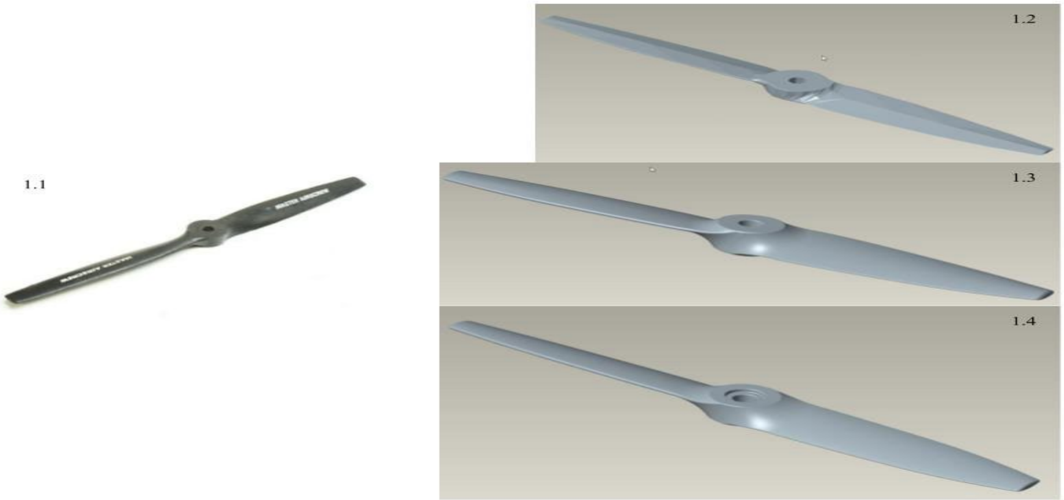


Figure 1. CAD Rendered Propeller Models. Figure 1.1 is the reference propeller. [9] Figure 1.2 is Design 1. Design 1 is a low thrust propeller, so small variations between LW-PLA and PLA counterparts would show a large effect on overall thrust-efficiency. Design 1 also has a comparatively lower initial angle of attack than the other propellers due to its thin structure. Figure 1.3 is Design 2. Design 2 has an overextended airfoil and a comparatively larger angle of attack than the other propellers. Figure 1.4 is Design 3. Design 3 was focused on midpoints between Designs 1 and 2. It has a lower initial angle of attack than Design 2, but it also has a higher initial angle of attack than Design 1. Propellers 3 and 4 were printed using Design 3, with the difference between them being layer line direction. All of the propellers were printed with the airfoil surface facing the print bed except for Propeller 4. Propeller 4 was printed with the attack surface of the propeller facing the print bed (See Figure 3).

Figure 2. Real-life side-by-side comparisons of LW-PLA and PLA counterparts of each design.
Note. The blue coloration of propeller PLA-1, the PLA variation of the model for Propeller 1 shown in Figure 1.2, does not affect the results of this study. The blue coloration is a result of cost reductions for this study. The propeller is still made of PLA and the physical and chemical properties of the propeller are unchanged as a result of differing pigment coloration for the purposes of this study.

Variables Addressed By Propeller Designs

Refer to Figure 1 for renders of each propeller. Propeller 1 has a small initial angle of attack and small airfoil (the flat surface of the propeller blade), making it a low thrust propeller (Figure 1.2). This propeller will be useful because small variations between LW-PLA and PLA variants will show a large effect on the thrust to efficiency ratio. Propeller 2 has a much greater angle of attack to account for the variable of a larger force along the thin attack surface of the propeller (Figure 1.3). Propeller 3 has a lower initial angle of attack to account for the variable of a larger force being applied along the airfoil surface of the propeller (Figure 1.4). All of these propellers (PLA and LW-PLA 1, 2, and 3) were printed as depicted in the images, with the blades supported using printed support structures to account for gravitational forces on plastic while printing.

An FDM 3D printer works by depositing material in 2D layers (x and y-axis). A completed 3D print consists of several of these 2D layers stacked along the z-axis to make a 3D object. Because of this, there are visible ridges (layer lines) along the z-axis that can affect the aerodynamics of the propeller. Propeller 4, depicted in Figure 1.5, was made using the same design as Propeller 3 but rotated so that the thin attack surface and trailing edge of the propeller would be parallel to the print bed while 3D printing to account for layer line direction and its effects on the aerodynamics of the propeller as a variable as shown in Figure 3. Refer to Figure 2 for a real-life comparison between LW-PLA and PLA variations of these propellers.

The design of these propellers is not an integral part of this study, as the goal of this study is to calculate the feasibility of using LW-PLA propellers over PLA propellers. An LW-PLA propeller simply has to generate a thrust-efficiency ratio statistically significantly greater than or with no statistical difference from a PLA propeller of the same design ($H_a < H_0$ or $H_a = H_0$).

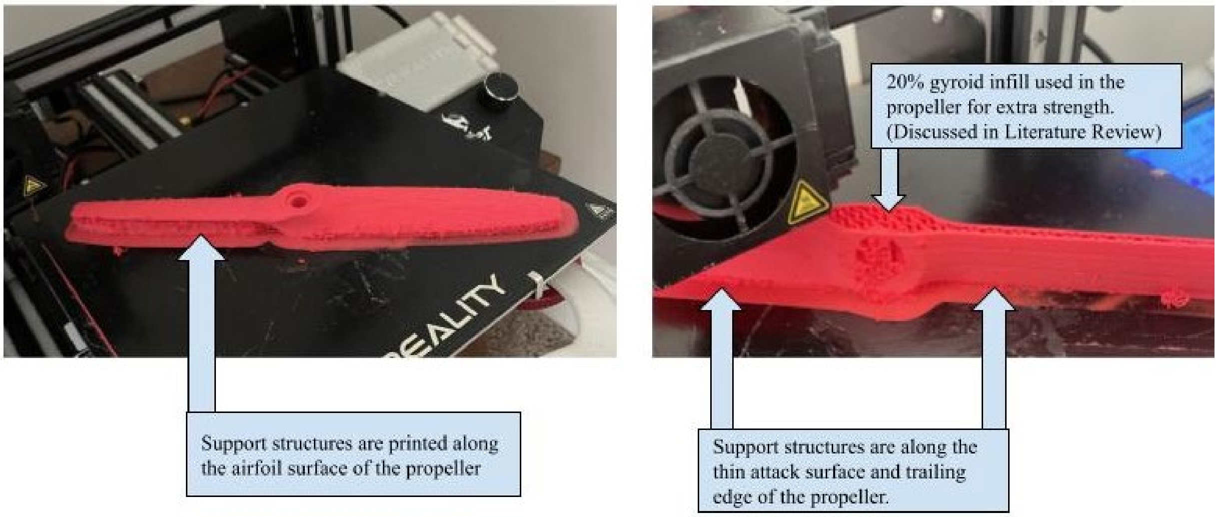


Figure 3. Real-life image of propeller printing orientation. Note. Propeller 1, 2, and 3 were printed in the orientation depicted on the left. Propeller 4 was printed in the orientation depicted on the right. The propellers depicted in these images are the LW-PLA variant of Propeller 2 (left) and the LW-PLA variant of Propeller 4 (right).

Finishing Methods

As stated in the literature review, LW-PLA absorbs surrounding air to create microscopic air bubbles. This creates a rough, porous surface, which disrupts the laminar flow of air over the surface of the propeller. While there is no current research addressing the strength of LW-PLA, it appears that its tensile strength is most likely less than PLA. Because of this, a second round of testing was done where all propellers, both LW-PLA and PLA, were coated with acrylic sealer, which would create a smooth airfoil surface for all propellers. Acrylic sealer was chosen as the coating method for its low cost and low density.

Thrust-Efficiency Testing

The test setup (wiring) being used in this experiment is similar to another study where the infeasibility of FDM propellers was found.[5] While Toleos Et. al. used expensive load cells to come to a conclusion, this study uses net torque measured on a scale using a lever and multimeter output, which mitigates high costs.

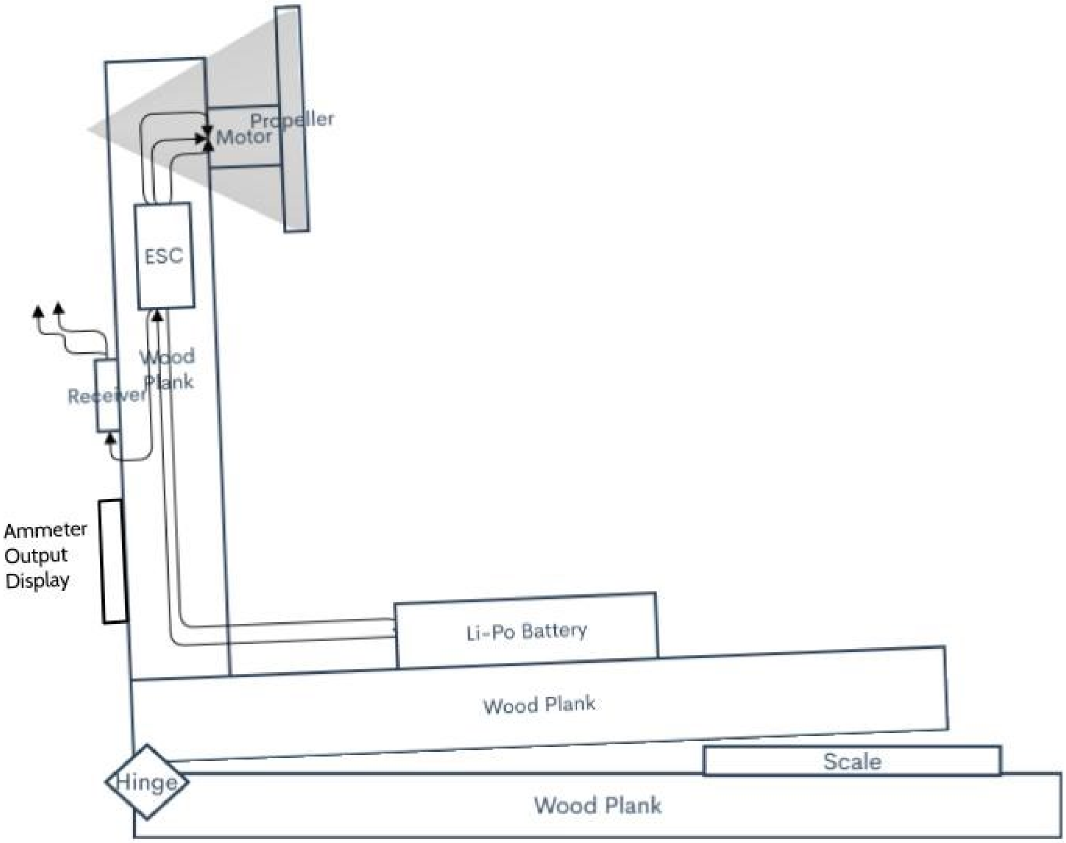
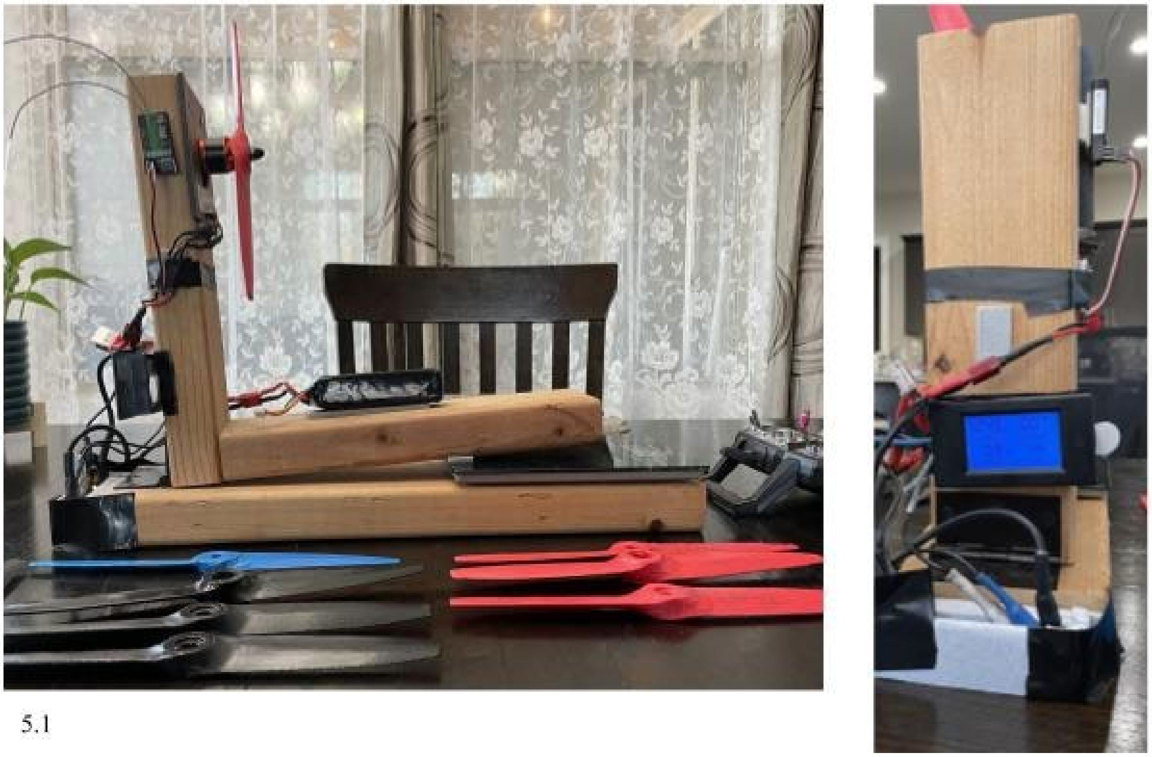


Figure 4. Diagram of thrust-efficiency testing apparatus.

Refer to Figure 4 for a diagram. When the propeller spins, it applies the force of thrust as shown by the light gray cone of thrust. When it does so, the hinge acts as a lever and transfers this force to the scale, where the applied force in Newtons was measured (See Equation 1 for detailed formula manipulation). A hardwired ammeter uses the Electronic Speed Controller (ESC), which takes direct current from the battery and supplies the necessary amperage to the motor, (Refer to Figure 5) to find the power draw (Amps) of the motor during testing. The power draw varies depending on how much power the motor requires in order to maintain a set RPM (half throttle was used so battery life lasts longer for more trials), and the weight of the propeller could cause this number to change based on inertia and torque. Both the highest power draw and highest thrust over a 10-second test period for each propeller were recorded. The data collection process was repeated for 10 trials for each propeller. An efficiency ratio was calculated by dividing the recorded thrust by the recorded amperage, $\frac{\Delta T}{A}$. See Equation 1 for more detail on formula manipulation. T-tests of the differences in thrust to power consumption ratio (thrust-efficiency) were calculated (PLA - LW-PLA).



5.1

5.2

Figure 5. Real-life application of thrust-efficiency testing apparatus. Figure 5.1 is the side view. Figure 5.2 is the rear view. Note. A 100A ammeter shunt was used to connect the ammeter between the Li-Po battery and ESC.

Equation 1. Net torque formula manipulation to calculate propeller thrust using thrust-efficiency testing apparatus.

Note. $F_{\text{scale(measured value)}}$ is the force from $\sum\tau$, which could be measured on the scale (See Figure 4).

$m_{\text{planks+propeller}}gsin\theta$ is the torque created by the center of gravity of the lever system (See Figure 4).

$$\tau_{propeller} = \sum \tau - \tau_{gravity}$$

$$\tau = Frsin\theta \ \ , F = ma, \text{ therefore } \tau = masin\theta$$

Going back to the first equation:

$$F_{propeller(Thrust)}r_{motor}\sin(90°) = F_{\text{scale(measured value)}}r_{scale}\sin(90°) - m_{planks+propeller}gsin\theta$$

Adding values of known constants and solving for $F_{propeller(Thrust)}$:

$$F_{propeller(Thrust)} = \frac{F_{scale}(0.21m) - m_{planks} +_{propeller}(9.8m/s^2)(0.174m)sin(12.528°)}{0.255m}$$

Results & Data Analysis

The TI-nspire CX CAS Student Software, simulating a TI-nspire CX II CAS calculator, was used to calculate all of the thrust-efficiency ratio significance tests, confidence intervals, and interval graphs used in this paper.

Thrust-efficiency Ratio

A thrust-efficiency ratio was calculated for each of the 10 trials for each propeller using the thrust formula described in the methods section divided by the amperage draw, ΔT/A. Then, the ratios of the LW-PLA variant of a design were subtracted from the ratios of the PLA variant of the same design (PLA - LW-PLA). For example, all thrust-efficiency ratios of propeller LW-PLA-2 were subtracted from all of the thrust efficiency ratios of propeller PLA-2. Then, a two-tailed t-test ($H_0 \neq H_a$) of the difference was calculated, with $H_0 = 0$. If the PLA propeller had a greater thrust-efficiency ratio than its LW-PLA counterpart, the values of the combined sample would be mostly positive, giving a low p-value. If the PLA propeller had a lower thrust-efficiency ratio than its LW-PLA counterpart, the same would occur. Only if the values were somewhat close would the p-value be great. The goal of this study was to find no significant difference between the usage of LW-PLA and PLA propellers.

PLA - LW-PLA

Table 1. P-values of t-tests on the significance of the difference in thrust-efficiency (PLA - LW-PLA)
Note. The predetermined α-level was 0.05.

Initial Tests (PLA-LWPLA) ($H_0 = 0$)	Two-tailed test ($H_a \neq H_0$) (Significant difference)
Design 1	3.243×10^{-9}
Design 2	3.385×10^{-8}
Design 3	8.553×10^{-11}
Design 4	6.732×10^{-11}

Table 1 shows the p-values for the difference in thrust-efficiency ratio in a two-tailed t-test. It is apparent that all of the p-values are below the predetermined α-level of 0.05. This means that H_0 can be rejected, meaning that there is a significant difference between LW-PLA and PLA propellers' thrust-efficiency ratio. In the process of calculating these p-values, it can be noted that the t-statistics for all of the designs were positive. This could indicate that the cause of the significant difference is that PLA propellers tended to have greater thrust-efficiency ratios than LW-PLA propellers.

PLA - LW-PLA (After Acrylic Coating)

Table 2. P-values from t-tests on the difference between the thrust-efficiency (PLA - LW-PLA) after coating with acrylic sealer.

Note. Predetermined $\alpha = 0.05$

After Acrylic Coating (PLA-LWPLA) ($H_0 = 0$)	Two-tailed test ($H_a \neq H_0$) (Significant difference)	One tailed test ($H_a < H_0$) (PLA is less)
Design 1	2.414×10^{-8}	N/A
Design 2	0.014	0.007
Design 3	0.038	N/A
Design 4	0.025	N/A

A second round of testing was conducted, where both the PLA and LW-PLA variants of each propeller design were coated with acrylic sealer. This would account for the effects of the microscopic air bubbles in LW-PLA increasing the drag friction on the propeller. The purpose of this second test was to determine if the lightweight properties of LW-PLA could be harnessed if the airfoil was more aerodynamic.

In this second set of trials, it can be noted that the p-values are much greater than prior to coating with acrylic (Table 2). Had the researcher chosen a lower $\boldsymbol{\alpha}$-level of 0.01 rather than 0.05, these results would show no significant difference between LW-PLA and PLA propellers once coated with acrylic. Changing the $\boldsymbol{\alpha}$-level after calculating the p-value is unethical. Because of this, H_0 is still rejected, meaning that there is a significant difference between the thrust-efficiency ratios of LW-PLA and PLA propellers of the same design even after coating with acrylic, which is held true for all observed cases. Interestingly, the t-statistic for Design 2 was negative, which prompted the researcher to calculate a one-tailed t-test to see if $H_a < H_0$. Design 2 after acrylic coating was the only instance in which an LW-PLA propeller had a significantly higher thrust-efficiency ratio than its PLA counterpart. For Design 1, it can be noted that the p-value is still extremely low. Though there is no current research on the flexural modulus of LW-PLA, the researcher did note that the material is more flexible than PLA qualitatively when in a thin form. Because Design 1 was a low thrust propeller, it was thinner than the other designs, which caused its LW-PLA variant to flex to a greater degree while being tested. A constantly changing airfoil creates drag friction, which reduces the thrust-efficiency of the propeller.

Overall Comparisons

In Figure 6, we can see an overall perspective of the thrust-efficiency ratios calculated for the study. Prior to coating, LW-PLA propellers had thrust-efficiency ratio intervals below or overlapping with the control (reference model, see Figure 1.1). After coating, every single LW-PLA propeller had a thrust-efficiency ratio greater than the control. The effectiveness of the acrylic coating can be visualized by this interval graph. The graph truly shows how much drag friction can decrease the thrust-efficiency ratio of a propeller.

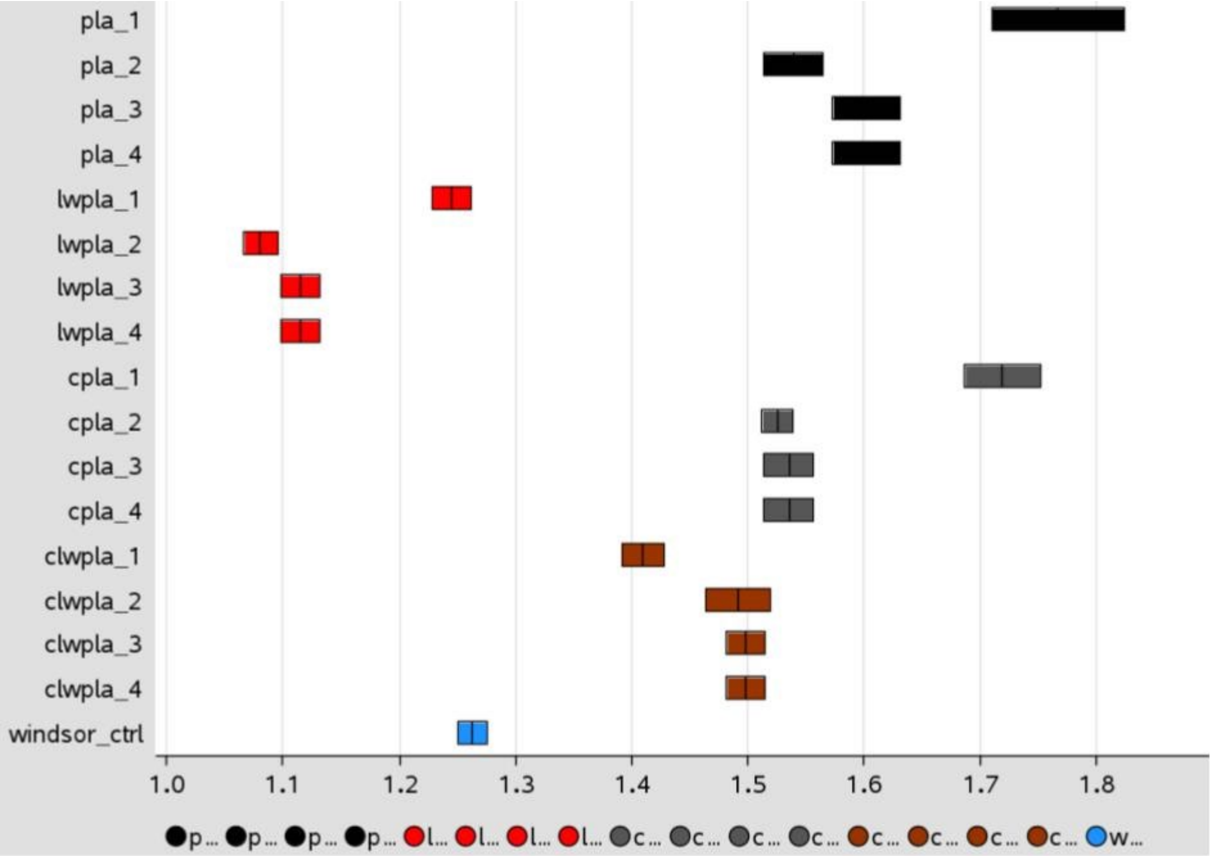


Figure 6. 95% confidence interval graph of of thrust-efficiency ratios of all propellers tested. Note. The prefix "c" indicates a propeller that had been coated with acrylic sealer. Windsor_ctrl refers to the reference model (Figure 1.1)

The researcher chose not to calculate a significance test between the weight of PLA propellers compared to the weight of their LW-PLA counterparts because the difference in mass was apparent to a great extent. For all designs, LW-PLA propellers were about 50% of the mass of their PLA counterparts (Figure 10). The weight reduction properties of LW-PLA were observed to a great extent in this study.

Conclusion

While LW-PLA propellers did produce a significantly differing thrust-efficiency ratio than their PLA counterparts, all of the LW-PLA propellers had a weight of about 50% of their PLA counterparts, even after coating with acrylic. The expansive lightweight properties of LW-PLA could still be used in propeller prototyping in applications where weight reduction is of higher importance than thrust efficiency.

According to Toleos Et. al., FDM PLA propellers are not feasible for manufacturing drone propellers due to their low impact strength. Interestingly, while injection-molded propellers certainly withstand a stronger impact, injection-molded propellers require a complicated and expensive manufacturing process. For prototyping, it is not feasible to create various molds of each propeller due to the high cost and labor involved. Toleos Et. al. state that FDM prototypes could be used to approximate the performance of injection-molded propellers when the print settings used by the study are used. While it has been proven that PLA propellers are feasible for prototyping purposes, this study proved that LW-PLA performs significantly differently from PLA in terms of thrust-efficiency ratio, so the same conclusion cannot be made about LW-PLA.

Limitations

Limitations of this study include the lack of funding and time. Instead of using a lever-based testing setup, a setup more similar to Toleos Et. al. using a thrust load cell to measure thrust could be used. Perhaps a commercial-grade license of ANSYS along with necessary training could be used to generate a computer simulation of an LW-PLA propeller. A high-quality 3D scan could have been done of the reference propeller (Figure 1.1) and PLA and LW-PLA propellers could have been compared by print setting rather than propeller design, similar to Toleos Et. al.'s study. All of these are incredibly expensive methods to perform this study. If more time were present, more trials could have been conducted, reducing the margin of error.

Limitations of the conclusion of this study include the connection between weight reduction and thrust-efficiency. This study did not directly attempt to find a connection between the two, but it was implied in that LW-PLA would simply be a lighter form of PLA. The torque of the motor at any given point was not measurable using cost-efficient methods, but it can be predicted to be a lesser amount for a lighter propeller using the formula

$\sum\boldsymbol{\tau} = \mathrm{I}\boldsymbol{\alpha}$ (Net Torque = Moment of Inertia * Angular Acceleration). Because the moment of inertia of the propeller would decrease for a lighter propeller while angular acceleration remained the same due to the fixed throttle speed, it can be predicted that net torque would be lesser for a lighter propeller. A lower net torque would mean that thrust-efficiency should be increased in theory because less torque, and therefore power, which is proportional to torque ($P=\boldsymbol{\tau}d/rt$, Power = Torque * Displacement / Radius * Time), would be used by the motor. Once again, this study did not attempt to record the Wattage of the propellers, but because $W/V = A$ (Watts/Voltage = Amperage), we can conclude that the wattage is directly proportional to amperage, which was recorded in this study. If torque and power can be related to thrust-efficiency ratio, as thrust-efficiency = $\Delta T/A$, then thrust-efficiency should be proportional to weight-reduction, as the Moment of Inertia decreases along with net torque. However, weight reduction proved to be about 50% in all cases where LW-PLA was used, but thrust-efficiency did not increase by 50% in those same cases. Because of this, LW-PLA cannot simply be considered to be a lighter form of PLA; it has its own unique properties that make it different from PLA. This conclusion assumes that LW-PLA and PLA are similar due to their similar chemical structure in order to perform comparative research, and the difference in physical structure is not accounted for. There is the exception of the second trial with acrylic sealer coating, which attempted to remove some physical differences between LW-PLA and PLA propeller airfoil surfaces, but even then, the thrust-efficiency did not increase by 50% in all cases for LW-PLA. There are physical differences between LW-PLA and PLA despite their similar chemical structure that were not completely accounted for in this conclusion due to the nature of this study being comparative research between LW-PLA and PLA propellers.

LW-PLA is still a novel material, and there is a wide range of research that could be done on the plastic. Firstly, a study of the tensile and flexural strength properties of the material, and how they change when varying infill patterns are used could be done. A study could be done on the complete physical and chemical properties of LW-PLA. As the acrylic coating was so effective in this study in reducing the drag friction of LW-PLA, perhaps a study could be done to find the coating that reduces the drag friction by the highest degree. These are just some of the unlimited possibilities that arise along with the introduction of an entirely new realm to the aerospace and materials science community.

In summary, LW-PLA had a significantly differing thrust-efficiency ratio to PLA, so the conclusions of Toleos Et. al., the standard for feasibility in this study, cannot be applied to LW-PLA. Therefore, LW-PLA is not feasible for prototyping injection-molded propellers in its current stage. This study is the preliminary research in the field of LW-PLA in aeronautical propulsion systems.

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