Development of a Quad Shrouded Rotor Micro Air Vehicle and Performance Evaluation in Edgewise Flow

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Abstract
This paper describes the design and development of a quad shrouded rotor micro air vehicle (MAV) and experiments to evaluate performance in edgewise flow. The aerodynamic efficiency of a conventional micro quad rotor is improved by incorporating a shroud structure. Proof of concept studies were conducted on 1.3", 1.6" and 2.6" commercial ducted fan systems. Comparison of a 2.6" shrouded rotor with an optimized unshrouded rotor showed a 30% improvement in power loading at a power input of 2 W. The shroud structure consisted of a machined foam diffuser with carbon fiber inlets attached. The total weight of the MAV was 104 grams with the shroud structure weighing 12 grams. The vehicle had maximum dimensions of 6”x6”. Successful hover flight testing of the vehicle was achieved using a proportional-derivative onboard feedback controller. Wind tunnel tests were conducted to assess thrust, drag and pitching moment of the vehicle in edgewise flight up to 4 m/s using a 6 component force transducer. For both the shrouded and unshrouded rotors, the thrust increased by 10% at 4 m/s, the drag had a quadratic variation with thrust and a linear variation with speed. The drag and pitching moment for the shrouded quad was up to 2-2.5 times greater than the unshrouded quad rotor. Control moment measurements suggested that the quad shrouded rotor had an edgewise gust tolerance of at least 4 m/s. The drag and thrust measurements were compared with data from another study (9.5" shrouded rotor) revealing that the performance of the shrouded rotor scales satisfactorily with size.

Introduction
There is an increased interest to improve current rotary wing micro air vehicle (MAV) designs in order to carry out operations that require platforms that are stable, and efficient in hover and low forward speeds. Of the various rotary wing configurations, quad rotors have received the widest interest among research groups. This can be attributed to a number of factors. Implementing rotor control through traditional swashplate schemes can be prohibiting due to difficulties in creating and integrating robust complex assemblies. Therefore, design and implementation of quad and multi-rotor configurations are fast becoming a popular choice in which rotors have a fixed pitch setting and control is achieved through rotor RPM variation. Other advantages of these aircrafts are convenient handling characteristics, low cost and simplicity (Ref. 1)

Commercial quad-rotor aircraft include the German Ascending Technologies (8" rotor diameter) Hummingbird, the Canadian Draganfly Innovations (12" rotor diameter) Draganflyer and the Chinese Silverlit Toys X-UFO (8" rotor diameter). These along with quad-rotor aircraft developed in the research community (Refs. 2-5) are shown in Fig. 1. The smallest among these are the CrazyFlie (20g, Epsilon Embedded Systems) and MicroQuad (50 g, University of Maryland, Ref. 5). At MAV scales, these vehicles are marginally unstable with increased maneuverability. Therefore most of the research on micro scale quad rotor systems has been devoted to accurate modeling of dynamics and development of control schemes (Ref. 2).

A drawback of the quad rotor system is reduced aerodynamic efficiency when compared with a similar sized single rotor system (Ref. 2). The rotors also operate in the low Reynolds number regimes which further deteriorate performance (Ref. 6). A previous study (Ref. 7) examined optimization of rotor performance and investigated multi rotor effects in the MicroQuad. In conjunction with these optimization studies, it is also possible to further improve the aerodynamic performance of these systems by enclosing the rotors in a shroud (Refs. 8-14). Pereira et al. (Ref. 11) investigated the effect of
incorporating four shrouds in a quad rotor vehicle (4” rotor diameter, 250 g). While they did observe performance benefits, the shroud was not lightweight and stiff, which prevented further vehicle development. Of the commercial quad rotors mentioned above, only the X-UFO has the rotors surrounded by protective ring structures. However the tip clearance between the rotor and ring is greater than 5% of the rotor diameter. The ring depth is only a few percent of the diameter. Therefore it is unlikely that the ring structure offers performance improvements. Therefore the feasibility of using shrouded rotors for a quad rotor configuration remains to be investigated, proven in concept and flight tested.

Based on the above, the objective of the present study is to improve the aerodynamic performance of micro-quad rotors (rotor diameter below 3”) by enclosing each rotor in a shroud. Design implementations and vehicle integration are discussed subsequently. Hover flight testing is then described. Well known issues with shrouded rotors are the adverse affects of edgewise flow/gusts on flight stability. Therefore in the final section, the performance of the quad rotor in edgewise flight is studied with and without the shroud through a systematic series of wind tunnel tests.

**Shrouded rotor principle**

In the shrouded rotor configuration, the rotor is surrounded by a cylindrical shroud or duct. The shroud has a rounded leading edge and a straight or tapered trailing edge, which form the inlet and diffuser sections of the shroud respectively (Fig. 2). Operation of the rotor creates a suction pressure gradient on the shroud inlet surface. As a result, suction force is generated, which results in an additional lift (Fig. 3). Therefore the thrust from the rotor and shroud contribute to the total thrust. It has been shown previously in larger scales (greater than 10” diameter) that the total thrust of the shrouded rotor for a given power input exceeds that produced by the unshrouded rotor alone by at least 15-20% (Refs. 9,10).

**Proof of concept**

The objective of this study is to improve the aerodynamic performance of micro-quad rotors (rotor diameter below 3”) by enclosing each rotor in a shroud. Based on the above, there is scope for aerodynamic improvements even at scales below 3”. Now there are a wide variety of commercial ducted fan systems at these micro scales that are available for fixed wing propulsion applications, which operate at high disk loadings (Fig. 2). For static thrust, the principle of operation of ducted fans is similar to that of the
shrouded rotor. However, to the authors’ knowledge, there are no known studies that exploit these commercial ducted fan units for VTOL capability. Therefore in order to ascertain the utility of the duct/shroud at sub-3” scales, proof-of-concept experiments were conducted with three commercial ducted fan units (Fig. 4). The shroud geometry shown above includes a straight diffuser section and an elliptic or pseudo-elliptic inlet. The rotor/fan geometry shown above is a typical profile used for these applications. They are multi-bladed and twisted with a high root pitch angle close to 35°. Also, the taper is marginal and the airfoils have a camber of about 2-3%. The airfoil design can be approximated to a circular upper surface and a flat lower surface. The aspect ratio of the 2.6” rotor blade is close to 3.

To assess the performance of these units, each of these rotors first tested with the shroud and then in the unshrouded configuration (Fig. 5). This order was adopted since the ducted fan units came with the rotor assembled inside the shroud with supporting struts which ensured a low tip clearance between the rotor tip and the shroud wall. For the unshrouded rotor, the struts had to be machined off before testing. Therefore to maintain the original tip clearance, which is difficult to do, the shrouded rotor had to be tested prior to the struts being removed. The tip clearances were within 3% of the shroud diameter. The different rotor configurations were tested using a micro-rotor thrust stand to measure thrust and rotor torque (Fig. 5). The rotor RPM was determined using an optical tachometer. A NI-DAQ USB hardware setup with 12-bit resolution at 1000 Hz sampling rate was used for data acquisition purposes. Each data point was determined from an average of three measurements. In order to prevent the rotor downwash from affecting balance measurements, the rotors were mounted such that the downwash was directed upward. The thrust measurements and torque measurements were accurate to within 4-5% of the averaged values even though the accuracy of the load sensors was higher.

Figure 6 shows a comparison of power versus thrust for the three shrouded rotor systems. It can be seen
that for each system, there is significant improvement in thrust for a given power in the shrouded rotor configuration. Additionally the expected quadratic trend between power and thrust is maintained and does appear scale invariant for both the shrouded and unshrouded rotor cases. In order to compare the relative performance between the different scales, it is instructive to re-plot the information in Fig. 6 with respect to power loading and disk loading. From Figs. 7(a) and 7(b) a couple of observations can be made. The net improvement in power loading for the shrouded rotor over the unshrouded rotor at a disk loading of 100 N/m² is about 50%, 45% and 40% for the 1.3”, 1.6” and 2.6” rotors respectively. The 2.6” and 1.6” shrouded rotors have roughly similar aerodynamic performance. This suggests that a deterioration in aerodynamic performance is observed as we move from the 2.6” to 1.3” scale, but it is not significant. The improvement in aerodynamic performance over the unshrouded rotor is clear and does not appear to be scale dependent.

Comparison with efficient unshrouded rotor
It may be argued that the aforementioned commercially available rotors are not optimized to operate in the unshrouded rotor configuration. Therefore improvements with a shroud may be exaggerated. Harrington et al. (Ref. 7) looked at optimizing the aerodynamic performance of a conventional micro quad rotor. The rotor diameter they chose was 2.6” which matches perfectly for the present application. The optimized rotor they found had the following properties: 2 bladed, solidity of 0.18 with a 6% camber circular arc airfoil and a root pitch angle of 18°. Using these rotor parameters, the optimum collective angle for the shrouded rotor configuration was determined to be about 30°. The reason for a high collective setting is that the induced velocity for the shrouded rotor is higher. The performance of the optimized unshrouded rotor was compared with the shrouded rotor in Fig. 8. It can be seen that at low thrust settings, there is no performance benefit with the shroud. At higher thrust levels, there was about a 30% improvement in thrust for a given power for the shrouded rotor. It is noted that this improvement is not as high as the values obtained for the commercial ducted fan units. This underlines the fact that the commercial rotors were not optimized for operation without the shroud. Nevertheless, the benefit is significant enough at thrust levels beyond 20 grams. Based on the above results, there is sufficient indication that the performance of the micro quad rotor can be improved by incorporating the shroud.

Comparison with 9.5” shrouded rotor
A previous study (Ref. 10) looked at performance improvements of a single rotor MAV by enclosing it in a 9.5” shroud (Fig. 9). It is of interest to see how the performance of the 2.6” shroud compares with the 9.5” shroud. Figure 10 shows a comparison of power loading versus disk loading for the two shroud cases. Data for the 9.5” shroud case is taken from Ref. 10. It can be clearly seen that the performance is very comparable across the wide scales (scale factor of 3.6:1). This is an important result since it gives the vehicle designer an expectation of power loading for a given disk loading for different shroud regimes and hence aid the design process.
Fig. 6(a). 2.6” commercial rotor performance

Fig. 6(b). 1.6” commercial rotor performance

Fig. 6(c). 1.3” commercial rotor performance

Fig. 7(a). Power loading, unshrouded rotor

Fig. 7(b). Power loading, shrouded rotor

Fig. 8. Comparison with optimized 2.6” unshrouded rotor

Data for unshrouded rotor taken from Ref. 7
Vehicle design and integration

Figure 8 can be re-plotted as a function of difference in thrust between the shrouded and unshrouded rotor for a given power input. This is shown in Fig. 11. For example, at 2 W of input, the thrust produced by the unshrouded rotor is about 20 g, while the shrouded rotor produces 26 g. Therefore, in a quad rotor system there is a net benefit of about 24 grams with the inclusion of a shroud. This implies that for net improvement in system efficiency the entire shroud structure should have a maximum weight of less than 24 grams.

Shroud structure design

The next step was to design an appropriate lightweight shroud structure that could be incorporated with the quad rotor. There are three feasible design concepts as shown in Fig. 12.

(a) Design-1: This is a direct approach where four individual shrouded rotors are taken and simply merged together with a central holding piece and/or epoxy. Now, each 2.6” commercial duct is constructed from plastic and weighs about 17 grams each (54 grams total), which exceeds the design limits. This implies that the commercial ducted fan systems cannot be used for the present design. The shroud can also be constructed from graphite-epoxy (Gr-Ep) material. However the density of the material is about 2.4 g/cc. A 30 mm diffuser section and 0.5 mm wall thickness would result in a total shroud weight of 36-40 grams. Another option is to use acrylic based photopolymer resin, with a density of 1.2 g/cc when cured. A significant advantage of this construction method is that changes in shroud design can be easily incorporated till acceptable performance and rigidity is achieved. However, this does not hold a given shape well as time progresses especially with thin walled structures. A warped shroud is not desirable. Based on these factors, it appears that design-1 would result in a prohibitively heavy shroud structure.

(b) Design-2: This represents a novel approach where the inlets are manufactured separately. It must be kept in mind that the inlets do not transfer structural load. Next, two foam plates with four diffuser pockets are spaced apart using carbon struts. This structure can be designed to be stiff, yet lightweight. Then, a cylindrical paper or plastic diffuser can be inserted into the foam pockets. The advantage of this design is that each structural member is designed individually based on its particular utility. As a result, the size can be scaled up without impacting the overall structural weight (need not obey the Mass \( \propto \) Size\(^3\) law). However the disadvantage is that there are multiple modes of structural failure which can affect integrity of the vehicle during hard landings. Additionally, for the proposed vehicle design size of 6”\( \times \) 6”, the weight difference between design-2 and design-3 is minimal.

(c) Design-3: This is a modification of design-2 where the inlets are again manufactured separately. However, the diffuser structure is manufactured entirely from polystyrene or polypropylene foam with four machined diffuser pockets. This offers good stiffness while being lightweight with density ranging between 0.03-0.1 g/cc.
Based on the previous discussion, the final design choice for the shroud construction incorporated Gr-Ep elliptic inlets using mold and furnace treatment (Fig. 13). These were mounted on an extruded polystyrene foam structure (Owen’s Corning PINK®) with four diffuser pockets (1” thick). The final quad shrouded structure along with the shroud inlets weighs about 12 grams (8 gram foam diffuser, 4×1 gram carbon fiber inlets) which is well within the weight constraints.

**Rotor structure design**

This component of the vehicle follows a conventional quad rotor design. A carbon fiber foam baseplate with 0.4” thickness is machined with mutually orthogonal arms. Four 2000kV brushless outrunner Hextronix motors are mounted at the ends of each arm (spaced about 3” apart). Custom made Delrin hubs with a root pitch angle of 30° are incorporated. The rotor blades are constructed from Gr-Ep with 6-7% camber circular arc airfoils. They are untwisted and have a rectangular planform. The solidity was 0.26. These blades were held to the rotor blades through steel pins. The motors were controlled by 6-amp Thunderbird electronic speed controllers. The final integrated vehicle is shown in Fig. 14 with the various subcomponent assembly. A breakdown of the vehicle weight is given in Table 1.
Vehicle performance testing
Now with the vehicle assembled, the next step was to verify performance improvements of the vehicle itself. These experiments were setup as shown in Fig. 15. Here the shroud structure was affixed to a thrust balance-1 via a system of carbon struts and Delrin supports. A second balance-2 was mounted above balance-1. Now balance-2 supported the unshrouded quad rotor. By orienting the balance-2 system carefully within the shroud, the entire shrouded rotor performance can be evaluated. Electrical power is measured for efficiency comparison. This setup also allowed a direct measurement of the rotor thrust, shroud thrust as well as total thrust. Figure 16 shows the breakdown of different thrust components as a function of the average rotor RPM of all the rotors. It can be seen that at high RPM values, the ratio of the shroud thrust to total thrust was about 45%. Figure 17 compares the thrust produced as a function of the electrical power input for the vehicle with and without the shroud structure. If the shrouded rotor vehicle weighs about 100 grams, the weight of the unshrouded rotor would be about 90 g. It can be seen from Fig. 17 that at these design points, there is about a 20% reduction in power required to achieve hover for the shrouded rotor vehicle. This clearly demonstrates the hover performance improvements of a conventional quad rotor by incorporating a shroud structure.

Hover flight testing
The next step was to carry out hover flight testing of the vehicle. Since the bare airframe dynamics of the quad rotor is unstable, a feedback control system is required to provide sufficient attitude damping and stiffness to achieve stable hover. For this purpose, a 1.5 gram
sensor-processor platform (GINA Mote) designed by University of California, Berkeley (Ref. 15) is incorporated as the onboard controller. The principal components of the board are a TI MSP430 microprocessor for onboard computation tasks, ITG3200 tri-axial gyros, KXSD9 tri-axial accelerometer, and an ATMEAL radio and antenna for wireless communication tasks. A breakout board is designed that allows for convenient transfer of control signals to the onboard actuators.

The conventional control strategy for the quad rotor is shown in Fig. 18. Appropriate variation of rotor RPM results in heave, pitch, roll and yaw motions of the vehicle. For stabilization purposes, a disturbance in vehicle attitude and attitude rate is fed back to the input using a proportional-derivative controller. For the states, the onboard gyro measure the pitch, roll and yaw attitude rates while the accelerometers record the tilt of the gravity vector. A complementary filter was incorporated to extract the pitch and roll Euler angles using a high pass filter for the gyro (4 Hz cut off) and a low pass filter for accelerometers (6 Hz cut off). Figure 19 shows the wireless telemetry setup. A 2.4 GHz ATMEAL AVR transceiver was attached to a base station. This was used to wirelessly update (IEEE 802.15.4 protocol) the feedback gains, trim inputs and attitude reference commands to the vehicle in flight. The control system implementation is shown in Fig. 20. The wireless communication has latency less...
than 20-30 ms. The time critical inner loop feedback occurs at an update rate of 3 ms. The user communicates with the vehicle using a LabVIEW interface.

Free flight testing involved a careful selection of trim values for the different rotor RPMs and the proportional and derivative gains that were tuned through the Ziegler-Nichols method. Finally the vehicle successfully achieved hover flight as can be seen in Fig. 21. Improvements in flight stability are currently underway by incorporating speed controllers with reduced delay and including motor dynamics in the control scheme.

**Edgewise flight testing**

The previous sections described the hover tests of the shrouded quad rotor MAV. The improvement in hover performance by incorporating a quad rotor with a shrouded frame resulted in a payload benefit of at least 10-15 grams. Now, it has been studied earlier that single shrouded rotor vehicles undergo an adverse pitching moment when they encounter edgewise flight or gusts (Refs. 16, 17) as shown in Fig. 22. It is of interest to see if this observation extends to multi rotor
shrouded vehicles at the MAV scale. This section will attempt to answer the following issues: (a) performance comparison between an unshrouded and a shrouded quad rotor, (b) direction sensitivity of a quad shrouded rotor in edgewise flight (shroud orientation) and (c) performance comparison in edgewise flow between a 2.6” and a 9.5” shrouded rotor for scaling effects.

**Experimental setup**

In edgewise flights, the main forces encountered by the vehicle are thrust, drag and pitching moment. In order to measure these, the vehicle was mounted on a 6 component force transducer (ATI Nano-17) as shown in Fig. 23. This enabled the measurement of thrust ($F_z$), drag ($-F_x$), side force ($F_y$), pitching moment ($M_y$), rolling moment ($M_x$) and yaw moment ($M_z$). The vehicle could be either mounted such that it is thrusting upwards or downwards. It was found that a thrusting upward configuration would be most appropriate for pitching moment measurements in edgewise flight. Therefore as shown in Fig. 23, sufficient gap between the shroud diffuser exit and ground plane was provided to avoid ground effect.

(a) **Comparison with unshrouded rotor**

For these tests, the vehicle was mounted in the shrouded and unshrouded rotor configuration with rotors 1 and 2 facing the exit of a 22”×22” open jet wind tunnel, which was used to generate edgewise flow as shown in Fig. 24. Performance at flow speeds of up to 4 m/s was studied. At each wind speed, prior to rotor operation, the effect of bluff body drag and moment were removed. Following this, a thrust sweep was conducted. At each thrust level, both thrust, drag and pitching moment measurements were made. These values represented the aerodynamic effect of operating a shrouded or an unshrouded rotor in edgewise flight while neglecting the effect of bluff body drag. The thrust was correlated with RPM which was pre-calibrated with the throttle setting of the speed controllers (Fig. 25). The throttle command to the speed controller is a pulse width modulated signal with the width of the pulse represented in milli-seconds. The throttle-RPM variation was determined to be quadratic. A curve fit represented the averaged value of the individual rotor RPMs at each throttle setting. This procedure was adopted since it was cumbersome to implement RPM sensors for all the four rotors without affecting the airflow in the rotor wake. It was seen that the throttle-RPM variation between the shrouded and unshrouded rotor configuration remained the same.

(b) **Direction sensitivity**

This is an important consideration since multiple rotors operating in edgewise flight are involved. Figure 26 shows the two main directions that a quad rotor can operate in edgewise flight: (1) rotors 1 and 2 forward (X), and (2) rotor 1 forward and rotor 3 backward (plus). Multi rotor effects were investigated with the plus-configuration as shown in Fig. 27. Here config-a (Fig. 27(a)) refers to rotors 1 and 3 in operation and rotors 2 and 4 switched off. Similarly config-b (Fig. 27(a)) refers to rotors 1 and 3 off and rotors 2 and 4 on. Config-c (Fig. 27(c)) implies all four rotors are switched on in the plus-configuration.
Fig. 23. Vehicle mounted on 6 component force transducer for force and moment measurement

Fig. 24. Setup to measure performance of shrouded and unshrouded rotor configuration in edgewise flight

Fig. 25. Calibration of throttle command with rotor RPM (curve fit represents averaged RPM)

Fig. 26. Two orientations of quad rotor operation in edgewise flight

(a) plus-configuration
(b) X-configuration
Fig. 27. Shrouded quad rotor tested in different orientations in edgewise (red arrows indicate rotors in operation)

Results and Discussion
(a) Effect of shroud
The differences in thrust, drag and pitching moment for the shrouded and unshrouded rotor vehicle are detailed here. For these tests, the vehicle was tested in the X-configuration (Fig. 26(b)). Figure 28 shows the variation of total thrust with average rotor RPM at different wind speeds for the shrouded and unshrouded rotor vehicles. For both the vehicles, the thrust variation was negligible from hover condition up to edgewise flow speed of 2 m/s. Beyond that, the thrust increased at a given RPM. At 4 m/s of edgewise flow and an operating RPM of 7900, there was a 12% and 15% increase in thrust over hover condition for the unshrouded and shrouded rotor respectively. The significant improvement in thrust for the shrouded rotor over the unshrouded rotor at each edgewise flow speed can be clearly seen. At 7900 RPM, the thrust produced by the shrouded rotor is about 20 grams higher.

Figure 29 shows the variation of drag versus thrust for the two vehicles. It can be seen that the drag (-F_d) increases significantly with wind speed for both the vehicles. Now a rotor operating in edgewise flight changes the direction of momentum of incoming airflow. From a conservation of momentum perspective, this results in a drag on the rotor system. The shrouded rotor causes a larger momentum drag since it changes the direction of momentum to a larger extent (due to the shroud diffuser). This is exactly observed in Fig. 30 where the drag on the shrouded rotor is up to 2-2.5 times that of the unshrouded rotor.

The thrust-drag appears to have a quadratic variation in the shrouded rotor configuration. Figure 31 shows variation of drag as a function of edgewise flow speed at about 8000 RPM. For both configurations, the drag appears to vary linearly with speed. These two observations, i.e., quadratic variation of drag with thrust and linear variation of drag with velocity can be reconciled with the momentum theory treatment of drag due to a shrouded rotor. From Ref. 17 the momentum drag, D, can be expressed as,

\[ D \propto v_1 V_\infty \]

where, \(v_1\) is the inflow velocity of the rotor and \(V_\infty\) is the freestream edgewise velocity. Now,

\[ v_1 = \sqrt{\frac{T}{2 \rho A}} \]

\[ \Rightarrow \frac{D}{V_\infty} \propto \sqrt{T} \quad \text{Eq.(1)} \]

In an attempt to collapse data shown in Fig. 29(b) the data is recombined using the above equation and is plotted in Fig. 32. As can be seen, the observation that the drag varies linearly with velocity and quadratically with thrust is verified satisfactorily.
Fig. 28. Effect of edgewise flow on thrust produced

(a) Unshrouded quad rotor
(b) Shrouded quad rotor

Fig. 29. Effect of edgewise flow on drag produced

(a) Unshrouded quad rotor
(b) Shrouded quad rotor

Fig. 30. Comparison in drag produced at 4 m/s edgewise speed

Fig. 31. Variation of drag with wind speed (8000 RPM)
The next measurement of importance is the pitching moment encountered by the vehicle in edgewise flow. The momentum drag has a significant contribution towards generating a pitching moment about the vehicle C.G. (Refs. 16, 17). Therefore, it is expected that the variation of the moment with edgewise flow be similar to the drag results. An additional significance of the pitching moment is that it determines the control authority required in order to negate it. This decides the limits of vehicle tolerance to edgewise flow. Figure 33 shows the pitching moment variation with thrust for the shrouded and unshrouded rotor. The variation of the pitching moment for the unshrouded rotor is not as significant as for the shrouded rotor. The pitching moments at 4 m/s were compared for the two configurations (Fig. 34). Similar to drag, the shrouded rotor produces up to 2-2.5 times the pitching moment of an unshrouded rotor. Using a similar method described in Eq. 1, the data from Fig. 33(b) was reduced and plotted in Fig. 35. With the exception of low speeds, the data collapsed fairly well at high wind speeds into a linear fit.

Assuming the shrouded rotor vehicle has an operating thrust of 80 gm, it can be seen that at 4 m/s, it has to generate control moments of at least 175 gm-cm to overcome the adverse pitching moment. Figure 36 shows the control moment of the shrouded rotor for a given control input. From an extrapolation of Fig. 36 it can be seen that at least 50% of the control input needs to be given to counter the adverse pitching moment at 4 m/s. Future work is required to populate the chart shown in Fig. 36 for higher values of control input. Therefore, it can be seen that the edgewise gust tolerance of the shrouded quad rotor is at least 4 m/s.

(b) Effect of shroud orientation in edgewise flow

These results refer to the experimental setup schematically shown in Fig. 27. Figure 37(a) shows the drag produced by the rotors as a function of thrust at 4 m/s of edgewise flow in the plus-configuration. It can be seen that ‘config-a’ generates slightly higher drag at low values of thrust, but the two configurations are comparable at high thrust settings. When all the four rotors are spun up in the plus-orientation, we obtain ‘config-c’. In this case, all the rotors may be aerodynamically interacting with each other. To observe the extent of interaction, ‘config-c’ is compared with ‘config-a’ and ‘config-b’ as shown in Fig. 37(b). In this figure, it can be seen that the amount of drag produced by all the four rotors in edgewise flight does not differ with the cumulative drag produced by the two pairs of rotors 1-3 and 2-4. Therefore, in terms of drag it can be concluded that interaction between rotors is minimal at least when the thrust setting is high. A similar observation can be made in terms of pitching moment as can be seen from Fig. 38. However, at low values of thrust, there is a difference, suggesting multi-rotor aerodynamic interaction effects. From Figs. 37 and 38, it was seen that the aerodynamic interaction effects for the different rotors in edgewise flight at high thrust settings were minimal. On similar ground, the sensitivity to edgewise flow was compared between the ‘plus’ and ‘X’ configuration. However, from Figs. 39 and 40 it can be clearly seen that there is no difference in drag or pitching moment between these two configurations. This implies that the vehicle would
Fig. 33. Effect of edgewise flow on pitching moment

Fig. 34. Comparison in pitching moment (4 m/s)

Fig. 35. Reducing data from Fig. 33(b)

Fig. 36. Longitudinal control moment generated by shrouded quad rotor
behave exactly the same if it faced edgewise gusts in the ‘plus’ or ‘X’ configuration. This is strictly true if there is no change in pitching inertia between the two configurations. However an assumption of constant inertia is reasonable. In conclusion, there appears to be negligible multi rotor aerodynamic interaction effects at operating thrust in edgewise flight.

\[(c)\ \text{Scaling effects}\]
A previous study (Ref. 18) looked at a similar elliptic inlet shroud geometry, albeit applied to a larger scale (9.5” rotor diameter) and in a single rotor configuration (Fig. 41). Measurements of drag and pitching moment were made. It is of interest to see if any scaling criteria can be drawn to compare the present quad shrouded MAV with the larger single shrouded rotor MAV. For the sake of comparison, only drag data will be considered.

Now, from Ref. 17, the shrouded rotor drag in edgewise flow can be expressed as,

\[D \sim \rho A w V_\infty\]

where \(w\) is the exit wake velocity and \(A\) is the rotor area. Rearranging the above equation for a constant edgewise flow velocity, we arrive at,

\[\frac{D}{A} \propto \frac{T}{\sqrt{A}}\]  

Eq. (2)

It must be kept in mind that for a quad shrouded rotor with an individual rotor area of \(A_i\), the total area \(A=4A_i\). Figure 42 plots the drag variation with thrust at 2 m/s for the 9.5” shrouded rotor and the quad shrouded rotor. Clearly, there is a wide difference in the values due to the differences in operating range of thrust. In order to
Fig. 39. Effect of plus or X configuration on drag (4 m/s)

Fig. 40. Effect of plus or X configuration on pitching moment, $M_y$

Fig. 41. 9.5” elliptic inlet shrouded rotor from Ref. 18

Fig. 42. Drag comparison between 10” and 2.6” shrouded rotor at speed of 2 m/s

Fig. 43. Drag data from Fig. 42 scaled using Eq.2
reconcile this, the data is replotted in Fig. 43 using the criteria from Eq. 2. It can be seen from Fig. 43 that the data collapses for the two shrouded rotor cases. Now, this is extremely interesting since the two data sets represent shrouded rotors of different scales with one being a single rotor and the other a quad rotor. Given this, the two configurations can be compared on the same scale using fairly simple scaling criteria from Eq. 2. This result is important since it allows the vehicle designer to estimate the amount of drag for an arbitrary shroud dimension (at least up to 10”).

Summary and Conclusions
The design and development of a quad shrouded rotor vehicle with an aim of improving hover performance of a conventional micro quad rotor is presented. The vehicle has a gross weight of 100 grams with maximum dimensions of $6'' \times 6''$. After accounting for the weight of the shroud structure (12 grams), the net payload benefit with the incorporation of the shroud was about 12-15 grams. The vehicle was successfully hover flight tested using an onboard feedback proportional-derivative controller. Since shrouded rotors are known to have an adverse response to edgewise flow, a systematic assessment was made to evaluate the quad shrouded rotor performance in edgewise flow through a series of wind tunnel tests. Some specific conclusions drawn from this study are:

1. Proof of concept studies with commercial ducted fan units of sizes 1.3”, 1.6” and 2.6” showed a 40-50% improvement in power loading over an unshrouded rotor.
2. Comparison of a 2.6” shrouded rotor with a 9.5” shrouded rotor showed that performance improvements offered by the shroud appear to be scale invariant.
3. A significant challenge in these systems is the weight of the shroud structure itself. The chosen shroud structure consisted of an integrated foam diffuser with pockets that were attached to four individual carbon fiber shroud inlets. It helped to bring the entire weight of the shroud down to 12 grams.
4. In edgewise flow, the shrouded rotor produced up to 2-2.5 times greater drag and pitching moment over the unshrouded rotor. Analysis of the available control moment suggested an edgewise gust tolerance of the shrouded rotor to be about 4 m/s.
5. Tests showed that the multi-rotor interaction effects between the individual shrouded rotors did not manifest at operating thrust levels. The shrouded rotor also appeared to be direction insensitive. This implies that the vehicle received the same magnitude of pitching moment if one rotor (plus-configuration) or two rotors were facing the flow (X-configuration).

6. Based on a simple scaling criteria, it was shown that the drag measurements compared well with those produced by a larger 9.5” shrouded rotor. This result is important since it allows the vehicle designer to estimate the amount of drag for an arbitrary shroud dimension.

Future Work
The hover flight characteristics of the shrouded rotor vehicle needs to be improved. A second version of the vehicle with a gross take off weight of 80 grams has been assembled with an improved motor-assembly. Flight testing of this vehicle needs to be conducted. Finally, unconstrained response to edgewise gusts have to be performed and forward flight demonstrated.

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References


