Adaptive Winglet Design, Analysis and Optimisation of the Cant Angle for Enhanced MAV Performance

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Abstract

Adaptive air vehicle structures are an interesting option for enhancing an air vehicle's performance. This has been shown to be true even for MAV where a variety of solutions with regard to adaptive wings and tails have been presented so far in the past. Within the paper to be presented here an adaptive winglet for a MAV of 40cm in span and 25cm in length will be described. This is the size of a bird where bio-inspiration has been a good source for generating the adaptive winglet idea. Based on a modular MAV design and a flexible CAD model being already available, the adaptive winglet with variable cant angle could be simulated, designed, realised and validated. The CFD simulations of the MAV with winglet were done for various flight conditions and represented by factors such as best aerodynamic efficiency, stability and manoeuvrability. Optimum winglet angle search for best performance was done by using Genetic Algorithms. In order to expand the limited data points without doing too much CFD simulation, a new technique of grey prediction (using the rolling model) has been applied. Results predicted with this procedure are rather close to CFD results, with slightly less than 10% error in general and the optimum winglet angle to be determined very much in accordance to reality. With all the data from different simulations and algorithms used a working prototype with the mechanism for an active adaptive winglet was realised and its performance shown in hardware.

1 Introduction

Most of the commercial long range aircraft has installed winglet to decrease the induce drag to save more fuel, this feature can be also found on the bird. Bird use its feather at wingtip as "multiple winglet", which can be seen Fig. 1. Each feather has different angle respect to the wing, and they are passively adapted to the different flight conditions, which is different from the fixed angle winglet in the conventional aircraft (only designed for cruise).

Such adaptive winglet feature can be studied and implemented on the platform MAV to evaluate its performance and usefulness.

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However, passive adaptive multiple winglet requires deep understanding of Fluid Structure Interaction, which is very time consuming and requires large amount of computational resources. In order to avoid the complexity of FSI, the problem is simplified to active control winglet (ie, no FSI effect).

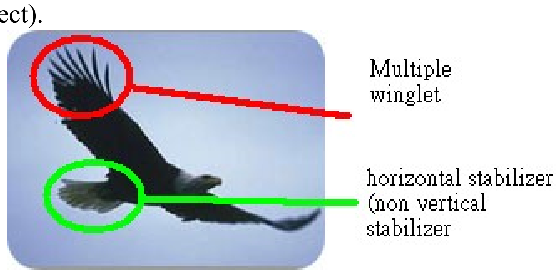

Fig. 1 A bird's wing during flight.[1]

Instead of having multiple winglets, one winglet on each side of the wing is used (like conventional aircraft), and angle of the winglet can be varied. Also, this setup can be the first step to understand the effect of the adaptive winglet.

2 MAV test platform

The test platform MAV has 40cm wing span with length of 25cm, detail dimension drawing can be seen in Fig. 2. The platform is stable with long endurance, which has been use to demonstrate and evaluate of different adaptive structures before [1],[2],[3]. therefore, it is very suitable platform for the study in this paper.

The MAV weights 200g (the test version), with flight speed of 8m/s. It has unique of vector thrust propulsion unit, allows the low energy consumption for entire flight.

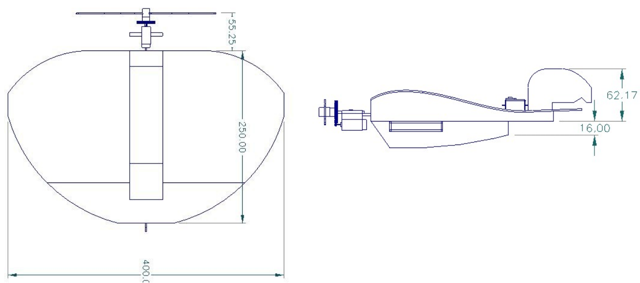

Fig. 2. The dimension of the MAV. Note: all units are in mm.

3 Development procedures

Since the MAV is quite a new field, therefore there is no

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actual research about the winglet size and angle, therefore, everything need to start from ground in this case.

There are varies adaptive structure has been design on the platform MAV; therefore, the adaptive winglet design must be able to be independently implemented on platform and integrate with other adaptive structures. For this reason, the adaptive winglet in with integration to platform is shown in Fig. 3

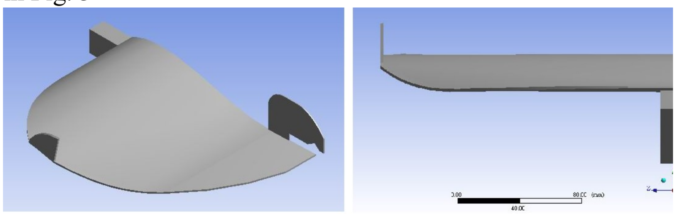

Fig. 3. Left, platform MAV with winglet (iso view). Right, back-view of the MAV with winglet.

However, instead simulate all the different angle of winglet, only few are selected to speed up the design and analysis process, and selected one are: -50,-30,0,20,45 and 65 degree, the CAD model of each can be seen in Fig. 4

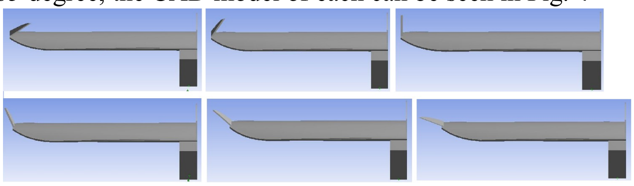

Fig. 4. CAD model of different winglet angle, from the top left to bottom right are:-50,-30,0,20,45,65 degree.

Because aerodynamic performance is not the only factor consider in this paper, therefore the simulation setup must consider varies different flight condition in order to evaluate factor such as stability and maneuverability [4].

CFD simulation assume the flow speed of 12m/s due to the propeller plus its own flight speed (ie the Re number is at 192,000). This condition has been proved in wind tunnel test in DLR in Göttingen.

Since the MAV geometry is complex, the use of K ω model become difficult and required high computational resources in storing the detail of boundary layer mesh, also, the simulation of the MAV flight is mostly with-in the stall region, therefore, standard K εmodel is selected for this study. The results has also be tested in the wind tunnel in DLR for aeroealsticity, the accuracy is of Fluid solid interaction simulation are well fit in around 5%, which shows the reliability of the CFD model. (please note, the model is not suitable for testing in stall region, which all the experimental and simulation are all carried out in pre stall region)

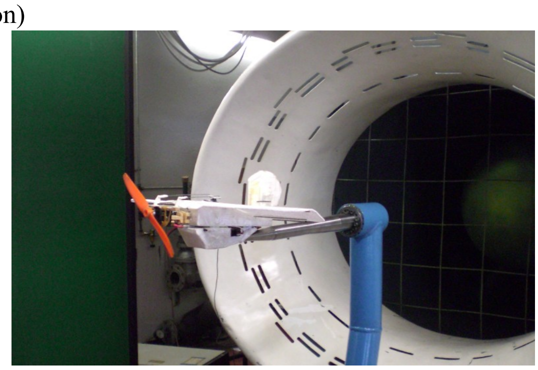

Fig. 5. Wind tunnel test model

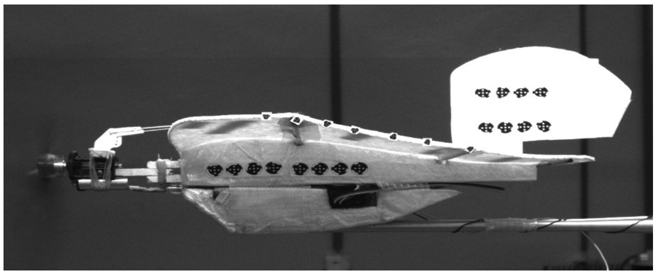

Fig. 6. The aeroelasticity test of the MAV in wind tunnel. Note. The marker system are provided by Fraunhofer ITB Germany.

For the fair test, all the mesh for CFD are kept constant in all simulation, boundary layer assume to be <15mm (by the experience). Hybrid mesh was used for boundary layer and air around it to reduce the computational resources,, and typically 2 million cell were in the mesh.

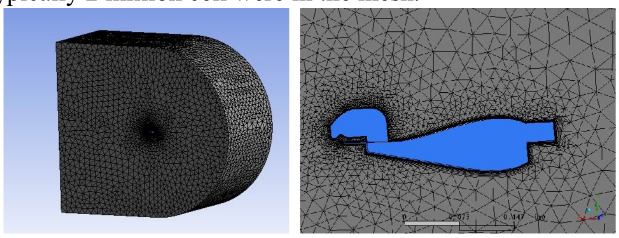

Fig. 7. Left, mesh of the flow region. Right, mesh around the MAV.

The overall design and development process block diagram can be seen in Fig. 8.

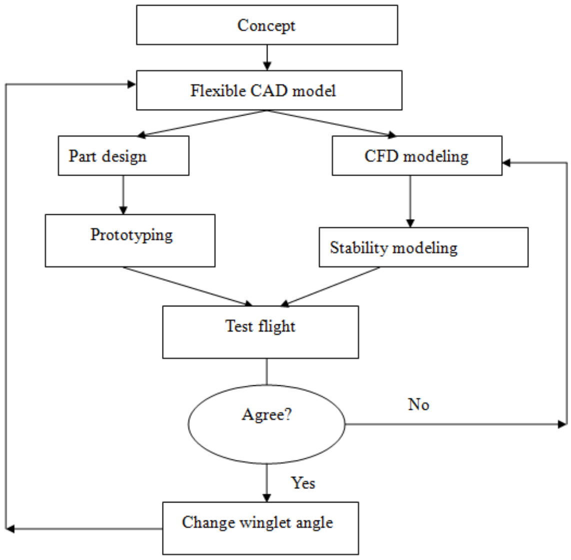

Fig. 8. Block diagram of the design and development process.

4 Numerical method

Genetic Algorithm

Genetic algorithm (GA) is a computational method for searching the solution of the optimal point. Traditionally, solution are represented in binary as strings of 0 and 1, therefore, the input value (analogue) in this case must convert to binary.

The algorithm starts from some randomly generated “Parents generation”, and fitness of every individual is evaluated, multiple individuals are stochastically selected from the current population, and modified (cross over and some randomly mutated).

In this case the input value is the angle of winglet, since the range is between 0 to 360 degree, therefore, 10 digit binary is selected as gene. In order to make sure there is optimal solution before end of generations, therefore, 100 generations are set.

Biologically, mutation only sometimes generate better offspring, therefore, the rate is set to be 10%, and cross rate is set to be 60%.

Base on the available data point, functions' are roughly estimated, and then G.A uses this function to search the maximum and minimum point (aerodynamic efficiency, stability and maneuverability).

Grey prediction

Grey predication is treating system as a grey system. In grey system theory, a dynamic model with a group of differential equations called grey differential model. The grey derivative and grey differential equation are defined and proposed in order to build a grey model.[5]

There are many different type of grey model, and common one are GM(1,N) and GM(1,1) model, Since data prediction is required, therefore GM(1,1) model should be selected, and by definition, at least four set of data is needed; in this case, the input is angle of the winglet, output is the stability and maneuverability, therefore, 6 data point can be collected (which satisfy the condition of using grey model). Equation (1.1) and (1.2) is the solution for GM(1,1) model.

$$\hat{x}_{(K+1)} = \left(x^{(0)}_{(1)} - \frac{b}{a} \right) e^{-ak} + \frac{b}{a} ,$$

$$\hat{x}^{(0)}_{(K+1)} = x^{(1)}_{(K+1)} - x^{(1)}_{(K)} \quad [1]$$

5 Results

CFD simulated results

The first simulated results include the winglet cant angle of 0, 20, 45, 65, -30, and -50. Each model has go tough series of CFD simulation for different flight conditions, results of longitudinal and lateral stability are compared with the MAV without any winglet. All simulated results are shown from Fig. 9 to Fig. 12.

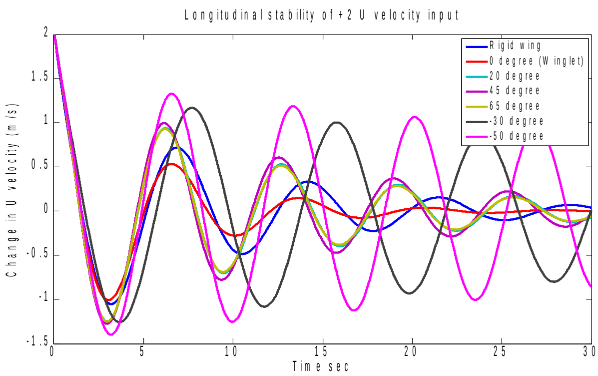

Fig. 9. Longitudinal stability results of the MAV (change in U velocity)

Longitudinal

All three different output results shows the most stable configuration is where the cant angle is equal to 0, and most unstable configuration is -50. Note: these results are only base on the simulated cases, which does not mean the definite results.

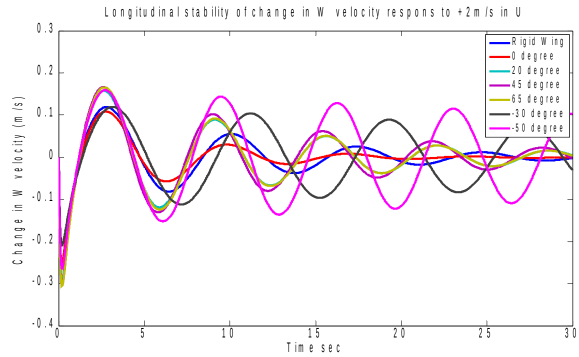

Fig. 10. Longitudinal stability results of the MAV (change in W velocity)

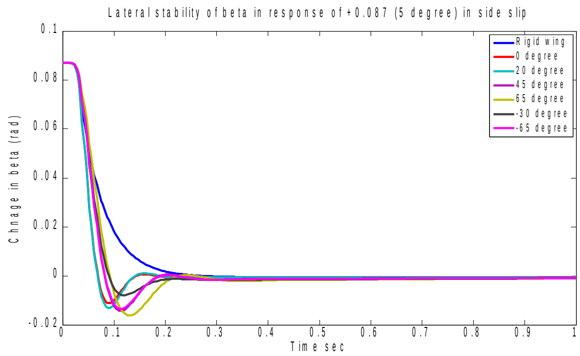

Fig. 11. Lateral stability results of the MAV (change in β)

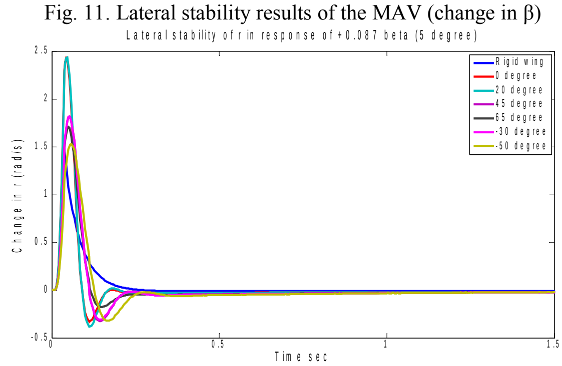

Fig. 12. Lateral stability results of the MAV (change in r)

Laterally

Simulated results in all cases shows the additional winglet cases damping ratio to drop, and MAV response to gust faster (but with overshoot). This is very logic, since winglet (doesn't matter which angle it is at) creates additional surfaces area in XZ plan (body coordinate system of the aircraft), and these additional surfaces cases additional forces and moment to be generated during lateral disturbance, in theory this should increase the speed of reaction, however, because the winglet in this experiment was located slightly in front of the C.G (due to the Zimmerman profile and vector thrust propulsion unit), therefore, the additional forces is resulting decreasing the overall damping ratio of the motion (speed up the response). This results also agree with Corneil's work in early 80s [6].

However, the with this increase in the response speed to gust, means decrease maneuverability, and from Fig. 11 and Fig. 12 shows the best maneuverability occur with 65 winglet configuration, where the response is slowest (if consider MAV with winglet configuration only).

Genetic algorithm search for best performance of the winglet angle

Since data obtain from the CFD simulation are limited, and with these limited data, one can only identify the best results from select cases.

However, the best results may not be in those exact cases (ie, best longitudinal stability may occur in 32 degree, which was not the simulated case). In order to solve this problem, genetic algorithm model was written for search the best aerodynamic performance, stability and maneuverability.

The research results shows from Fig. 13 to Fig. 15, and compiled results table is shown at Table 1.

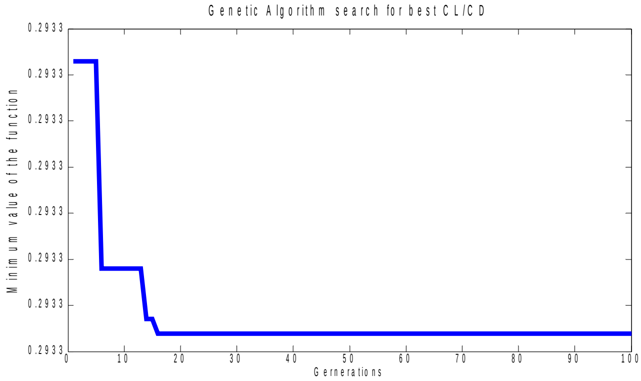

Fig. 13 G.M search of minimum value of the function for CL/CD

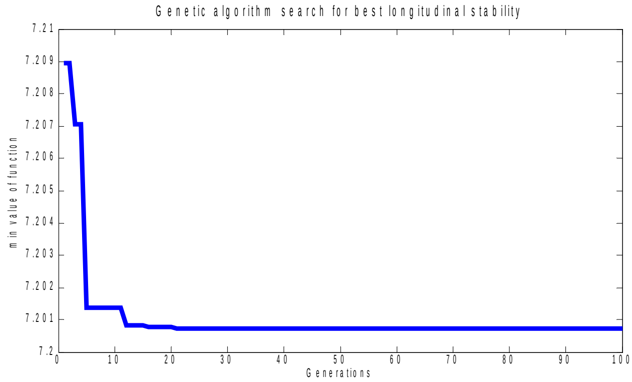

Fig. 14 G.M search of minimum value of the function for Longitudinal stability (base on the damping ratio of the motion)

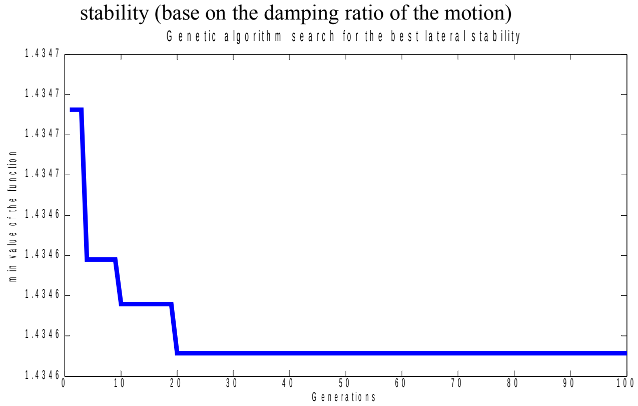

Fig. 15. G.M search of minimum value of the function for lateral stability (base on the damping ratio of the motion)

	CL/CD	Longitudinal stability	Lateral stability
Max (at degree of winglet)	35.6452	0	-39.638
Min	-41.16	-42	65

Table 1. Results of G.M search for best and worst performance of the variable angle winglet angle. Note: min stability represent best maneuverability.

The results from the G.A clearly shows some data that was not visible by just looking at selected CFD cases, and these information can be used for further autopilot design data base or pilot.

Using combination of Grey prediction and Genetic algorithm for searching best performance

G.A model is base on the already know data point and functions to search the best results, however, more data point it has, more accurate the function can be, hence, more accurate the G.A results will be.

As mentioned before, Grey prediction (G.P) uses the numbers of exciting data to predict the next set of data, which is completed different to G.A. In this project, rolling model method is used, and results is shown at table 2

Angle of winglet	Longitudinal damping ratio	Lateral damping ratio
-50	0.0176	0.53689
-30	0.024	0.648
0	0.1378	0.5594
20	0.09	0.5275
45	0.0787	0.52334
65	0.09411	0.507812
85	0.1074	0.4761
105	0.1163	0.4554
125	0.0995	0.4430
145	0.0983	0.4107
165	0.0970	0.3907
185	0.0958	0.3717

Table 2. The results of grey prediction of the damping ratio for both longitudinal and lateral motion. Note: black shows CFD results, and orange shows the G.P value. Note: 180 degree is not the same as 0 degree, see figure.2 for the orientation angle of the winglet.

Results from the G.P are later used in the G.A modeling. Even the data now is bigger; solution still converged before it gets to the default number of generation (100 in this project), results are shown in Fig. 16,Fig. 17 and compiled results in Table 3.

Even though the longitudinal results from Table 3 and Table 1 shows very similar, there is still have some slightly variation. However, the story is completed different in the lateral mode; there is 5 degree different for the max stability, but completely different story about the minimum stability.

The main reason for such different is because before G.P modeling, the data point is only up to 65 degree, and according to the data collected, which is not enough for G.M to solve the case, therefore the search stop at 65 degree. With G.P model, the data expanse to 185 degree, and with sufficient data point, much better G.A search can be preformed.

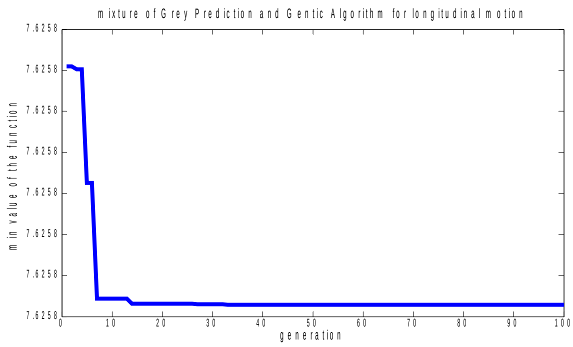

Fig. 16 Mixture of G.P and G.M search of minimum value of the function for longitudinal stability (base on the damping ratio of the motion)

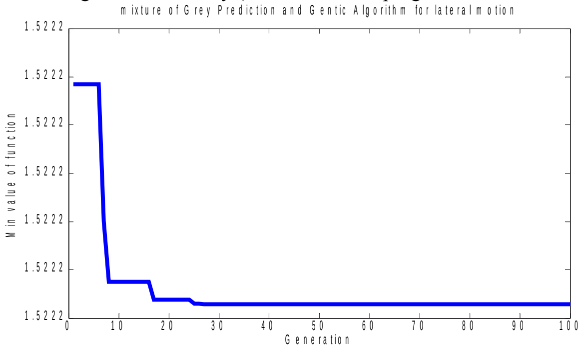

Fig. 17. Mixture of G.P and G.M search of minimum value of the function for lateral stability (base on the damping ratio of the motion)

	Longitudinal stability	Lateral stability
Max	-3.0158	-34.3046
Min	-43	185.1678

Table 3. Results of mixture of G.P and G.M search for best and worst performance of the variable angle winglet angle. Note: min stability represent best maneuverability.

Aerodynamically, the best efficient shows at 35.65 degree, which if recall Fig. 1, bird's winglet angle is not at 90 degree during the steady flight. In fact, when eagle is during the steady flight, the winglet angle is around 30 to 40 degree [7], which is in the range results obtain from this project.

Looking stability/maneuverability, longitudinally, the best stability at 0 degree and best maneuverability is at round -42 to -43 degree. Bird's winglet can not go to negative degree, since it is only control passively, but if consider the shape of wing during when bird during dive to attack on its target, the wing is rather at "M" shape [8]. This M shape decreases the lift coefficient, and vortex center move more toward to the body side (where the weight is), this similar effect can be seen when the winglet is at negative angle (Fig. 18), and therefore, it makes the bird and MAV easier to move in the longitudinal direction.

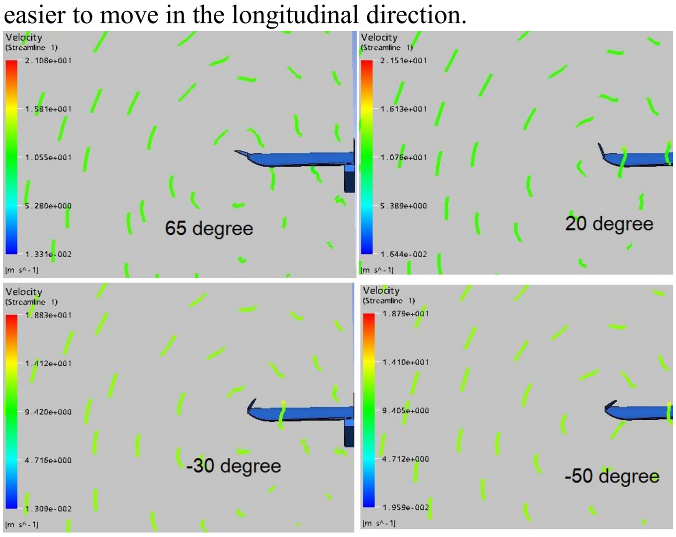

Fig. 18. The stream line of MAV with different angle of winglet. Note: the location of the vortex center is clearly different.

Laterally, results of CFD simulation shows the configuration without winglet has best stability, reason has been discussed before. However, if looking at winglet configuration, the best stability occurs at -34 degree from the G.A, and -39 degree with G.P & G.A modeling. Max maneuverability occur at the 187 degree. The reason for this effect is also to do with where the lift location and value. When lift is closer toward to the body, the moment for the lateral motion decreased when the same disturbance occurs, therefore the MAV resist the change.

All the results in the study indicate that all the best performance of MAV occur at different angle of winglet, therefore, for the in order to achieve most efficient flight, active control of winglet is required, and results from this study can be used for future autopilot design.

One other discovery in this study was that even use asymmetric variable angle winglet for maneuver is not efficient enough. Consider MAV with left side of wing has winglet of 90 degree (flat), and the right side of 0 degree, then the lift one the left is higher, which cause the rolling moment to the right, but side down wash on the right side is lower (because of the winglet), this will make the yawing moment to the left, therefore it is in conflict with rolling moment created.

Further more, when MAV is turn left with this configuration, the right side winglet is acting like vertical tail, which will generate side force to the right to resist the rolling moment. These motion can be seen in Fig. 19, and was also confirm with Bourdin's [9] and Corneil's [6] work.

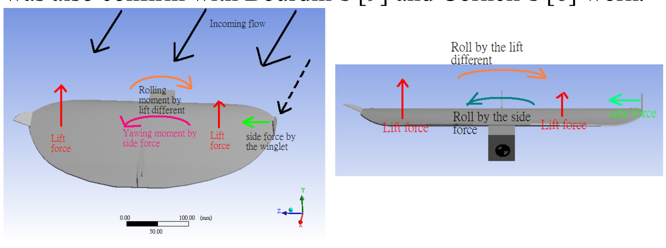

Fig. 19. Asymmertic winglet MAV during the turn. (front view at right)

6 Hardware Prototyping

Since the individual moment of winglet does not have any benefit (can see from Fig. 19), therefore, 2 winglet must be able to varies its angle together. For this requirement, only one servo is needed.

The condition is very similar to the Ref[1], therefore only small modification is needed form the original design.

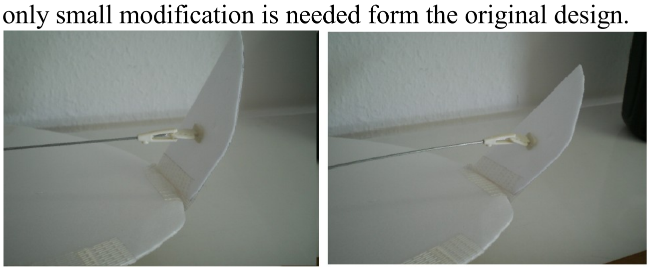

Fig. 20. The deflection of the winglet on the MAV. Note the mechanical linkage.

7 Conclusion

Study in this project shows the how the with a simple winglet configuration, the overall performance of aerodynamic efficiency, stability and maneuverability can be changed. Optimal angle of aerodynamic, stability and maneuverability performance has been identify with use either CFD data only, G.A only, and mixture of G.P and

G.A.

Traditional design and analysis process is time consuming, however, using limited data point from CFD, using mixture of G.P rolling model and G.A generating more data point, and search the optimal point is fast and more efficient.

Optimal angle for aerodynamic performance is around 35 degree. Longitudinally, most stable at 0 to -5 degree, and most maneuverable at -42 to -43 degree. Laterally, most stable at -34 to-39 degree, and most maneuverable at 185 degree. These results pattern also confirm with the natural bird's flight.

8 Future work

This paper shows the optimal angle for MAV performance, these data can be given to the autopilot design or flight programming.

Second step, with optimal angle and aerodynamic data known for the max CL/CD, therefore, passive winglet development can be possible.

Lastly, in order to get even more bio-inspired, both active and passive multiple wing let can be design and develop for the future.

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