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DEVELOPMENT OF A COMPREHENSIVE ANALYSIS AND OPTIMIZED DESIGN FRAMEWORK FOR THE MULTIROTOR UAV

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Abstract

Application field of the multirotor UAVs becomes broad, such as photography, agriculture, leisure, sport, and delivery. In addition, there are growing demands for application of the multirotor UAVs in lifesaving, disaster prevention, and military operation. For the analysis and design of the multirotor UAVs, methods and tools in previous studies could not propose the optimized components that were relevant for requirements of a mission. To establish a systematic and mission-intensive design procedure, this paper aims at developing an optimized design framework for multirotor UAVs. Conceptual Layout Optimization for Universal Drone Systems, CLOUDS, was developed based on multi-disciplinary analysis, including aerodynamic analysis of propellers, electric system analysis, and structure analysis. Then, accuracy of the analysis was validated, compared with experiment data and flight tests. In addition, optimized solutions of the multirotor UAVs for maximizing hovering time and range were investigated. As a result of the design, multirotor UAVs were optimized based on multi-disciplinary analysis.

1 Introduction

Multirotor UAVs can be made by the simple combination of several components such as propellers, brushless DC (BLDC) motors, electric speed controllers (ESC), a flight control computer(FCC), batteries, and frame. The controllability of multirotor UAVs has been improved due to advanced control techniques and development of FCC. Due to the wide market of the components and feasible control systems for the multirotor UAVs, application field of the multirotor UAVs becomes broad, such as photography, agriculture, leisure, sport, and delivery. In addition, there are growing demands for application of the multirotor UAVs in lifesaving, disaster prevention, and military operation. To perform these various missions, the multirotor UAVs should be designed to allow mission requirements in conceptual and preliminary design level.

For the comprehensive design of the multirotor UAVs, performances of the multirotor UAVs are analyzed. The performances can be evaluated by analyzing the thrust generated by rotating propellers and electric power consumed by the electric motors. Since the performance of multirotor UAVs is highly dependent to the interaction between aerodynamic resistance of the rotor and electric system of the BLDC motor, it is necessary that both rotor aerodynamics and electric system of the BLDC motor should be concurrently analyzed. Also, structural analysis is needed to calculate the stress of frame. Such multi-disciplinary analysis is capable to evaluate the overall performances, not only rotating speed, consuming power, and efficiency of motors but also flight time for a given mission.

The performance analysis of multirotor UAVs has been studied. Winslow, J.[1] showed individual components weights of the multirotor UAVs were estimated based on commercial products. Also, required mechanical power of propellers was analyzed using blade element momentum theory(BEMT). eCalc, Web-based analysis tool of multirotor UAVs, estimated drive current, electrical power, motor efficiency, and flight time of a multirotor UAV. This tool referred to the performance of the commercially available products. However, these analysis methods were unsuitable for the design that components of a multirotor UAV were undetermined. Bershadsky, D.[2] presented Electric Multirotor Sizing Tool(EMST) based on multi-disciplinary analysis, including aerodynamic and electric system analysis. The weights of the components and overall performances of a multirotor UAV were estimated using Blade Element Momentum Theory(BEMT) and electrical circuit analysis. However, the electrical power consuming motors were analyzed based on the fixed efficiency of motors. Because the efficiency could vary with respect to required performances in various mission segments, the design method was inappropriate for mission-intensive design. These analysis methods and tools could not propose the optimized components of a multirotor UAV that was relevant for requirements of a mission.

To establish a systematic and mission-intensive design procedure, this paper aims at developing an optimized design framework for multirotor UAVs. The framework, Conceptual Layout Optimization for the Universal Drone Systems(CLOUDS), proposes the optimized components of a multirotor UAV for a given mission profile. To develop the framework, overall design procedure was established based on multi-disciplinary analysis, including aerodynamic analysis of propellers, electric system analysis, and structure analysis. Then, accuracy of the analysis was validated, compared with experiment data and flight tests. In addition, optimized solutions of the multirotor UAVs for several missions were investigated.

2 Methodology

2.1 Overall Flow of Design Procedure

CLOUDS consists of two parts: multi-disciplinary analysis and optimization as shown in Fig. 1. A mission profile, one of the inputs of CLOUDS, is broken down to several mission segments. Design variables are specifications of the components which are propellers, motors, batteries, and ESCs. Once the design variables are determined, the multirotor UAV whose components are design variables is estimated its gross weight and analyzed in each mission segment. Then, battery capacity consumed in each mission segment is calculated and objective function of design problem is evaluated. Such mission segment analysis can reflect various mission requirements like speed of advance, endurance, or additional weight and current of payloads. Based on genetic algorithm, other design variables are changed and iterated such process until the maximum generation is reached.

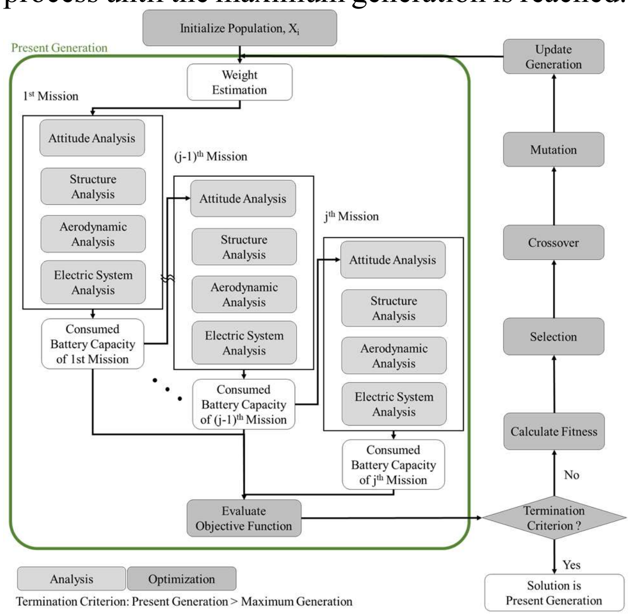


Fig. 1. Overall design flowchart of CLOUDS.

Most component weights are estimated by curve fitting data of Bershadsky, D.[2] except for the motor weight as in Fig. 2. The data of motors are commercially available products from eCalc and the curve fitting result is Eq. (1).

$$W_M=252,538(KV)^{-1.152},\ g \qquad (1)$$

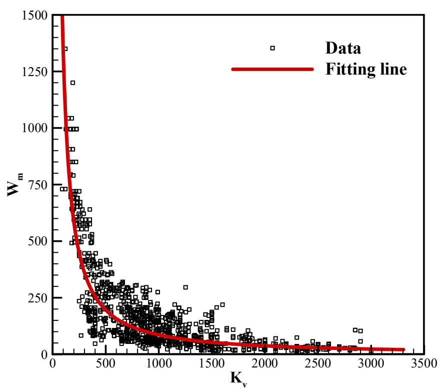


Fig. 2. Weight estimation of BLDC motors.

2.2 Mission Segment Analysis

Required battery capacities for each mission segment are calculated based on estimated gross weight through the attitude, aerodynamic, and electric system analysis. Fig. 3. shows input and output of each module. Attitude analysis module calculates the thrust required in propellers with respect to maneuvering type which are hovering, climbing, descent, and forward flight. After input of the required thrust, structure analysis evaluates the fracture of frame-motor support bars in given their cross section. Also, aerodynamic analysis module calculates rotating speed and mechanical power of propellers.

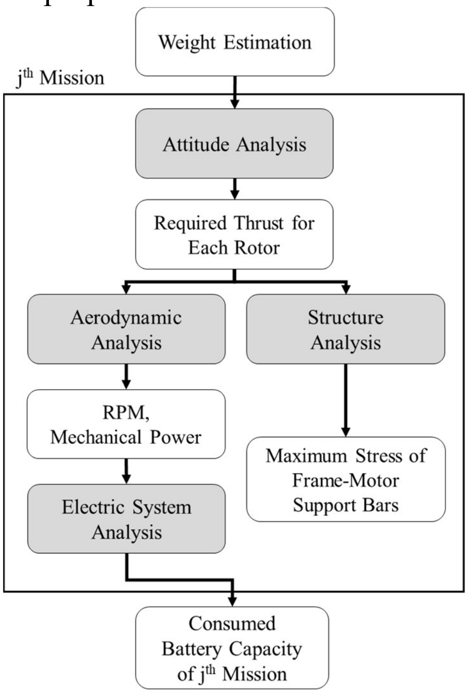


Fig. 3. Mission segment analysis

2.3 Analysis Modules

1) Attitude analysis: From estimated gross weight, required thrust for each rotor and pitch angle of the multirotor UAV are calculated. When the maneuvering type is hovering, climbing, and descent, the required thrust is identical to all propellers. However, the thrust is different between rear and front propellers in forward flight type due to the position of center of gravity. The pitch angle, θ is iteratively calculated using Newton-Raphson method in Eq. (2,3).

$$D = q_\infty S C_D(\mathrm{Re}, \theta) \tag{2}$$

$$\theta = \tan^{-1}\frac{W}{D} \tag{3}$$

Frame drag coefficient is one of the design parameters. It was deduced from wind tunnel test of a DJI Matrice 100 model by Korea Aerospace Research Institute (KARI). Forward flight is regarded as climbing due to larger pitch angle and stronger inflow ratio of propellers than the rotors of conventional helicopters. Also, the forward flight follows steady level flight and required thrust is analyzed as shown in Fig. 4.

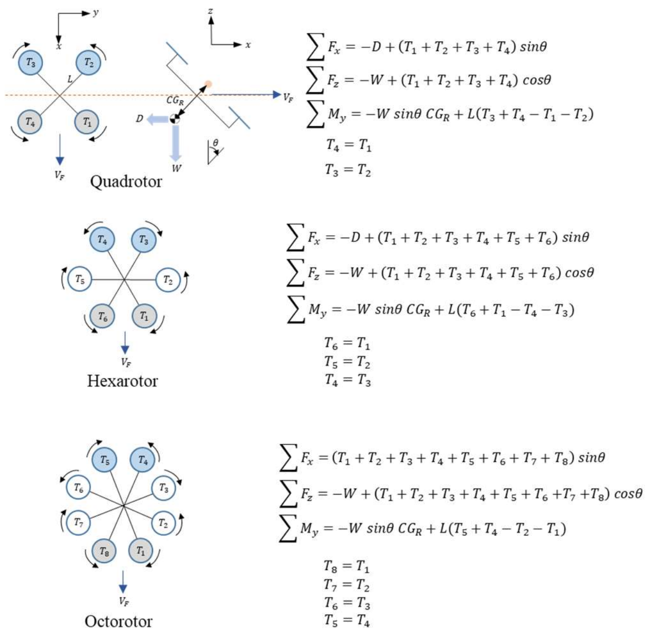


Fig. 4. Attitude analysis

2) Aerodynamic analysis: From required thrust calculated by attitude analysis, rotating speed and mechanical power of propellers are analyzed using Blade Element Momentum Theory(BEMT[4,5]) in Eq. (4-7).

$$dC_{T,BET} = \frac{1}{2}\sigma C_l r^2 dr \tag{4}$$

$$dC_{T,MT} = 4\lambda(\lambda - \lambda_c) r dr \tag{5}$$

$$C_T = \int_X^B dC_T dr \tag{6}$$

$$C_P = \int_X^B \kappa dC_T + \int_X^1 \frac{1}{2}\sigma C_d r^3 dr \tag{7}$$

As the design parameter, airfoil of propellers is Clark Y whose 2-D aerodynamic performances are analyzed by Xfoil[6]. Also, 10 parameters of a propeller blade are defined in Fig. 5. to parametrize the configuration of the blade.

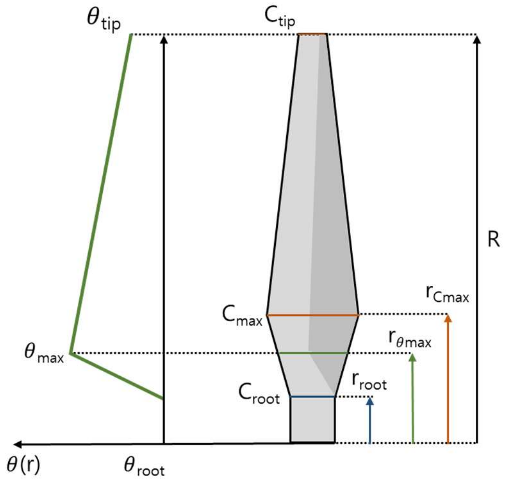


Fig. 5. Linearized propeller blade

Tip loss factor, B is 0.91 and induced power factor, κ is 1.23. Both factors were estimated from KPROP1-1 experiment data tested by KARI as shown in Fig. 6. and its configuration is shown in Appendix A.

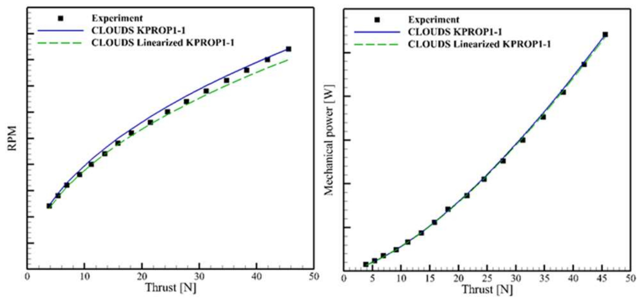


Fig. 6. RPM and mechanical power of KPROP

3) Structure analysis: Maximum stress of frame-motor support bar shown in Fig. 7. is evaluated in whole mission segments. The set of design variables which generates the thrust breaking the bars is unfeasible solution and such set is evaded in optimization procedure in CLOUDS. The bar is a cantilever beam whose length is proportional to the radius of propeller and the required thrust is generated at the tip of bar.

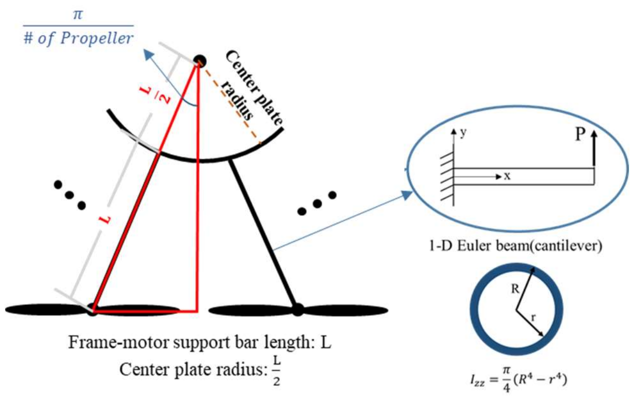


Fig. 7. Schematic of structure analysis

4) Electric system analysis: Based on the rotating speed and the mechanical power of the propeller, it is capable to calculate the drive current and efficiency of the motor. For this, it is necessary to estimate the internal resistance and no-load current of the motor as the design parameters. The trend of the motor parameters can be presented by the constant speed and weight of the motor as shown in Fig. 8.

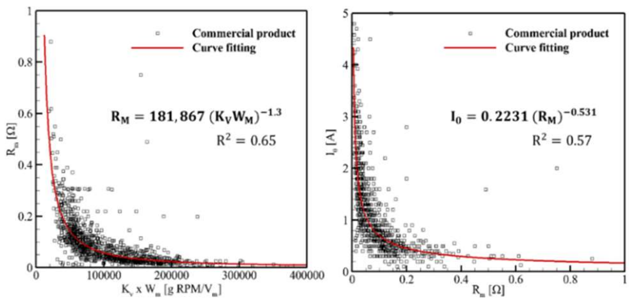


Fig. 8. Trend of internal resistance(left) and no-load current(right) of BLDC motors

Schematics of electric system is shown in Fig. 9. Required electrical power, P_E and motor efficiency, η_M were calculated, considering not only the required mechanical power, but also copper, iron loss, mechanical loss, and stray loss in Eq. (8-11) and [7,8].

$$V_M = V_B - I_M(R_E + R_B N) \tag{8}$$

$$P_{Co} = I_M^2 R_M \,, \;\; P_{Ir} = (V_M - I_M R_M) I_0 \tag{9}$$

$$P_E = P_{Mech} + P_{Co} + P_{Ir} + P_{ML} + P_S \tag{10}$$

$$\eta_M = \frac{P_{Mech}}{P_E} \tag{11}$$

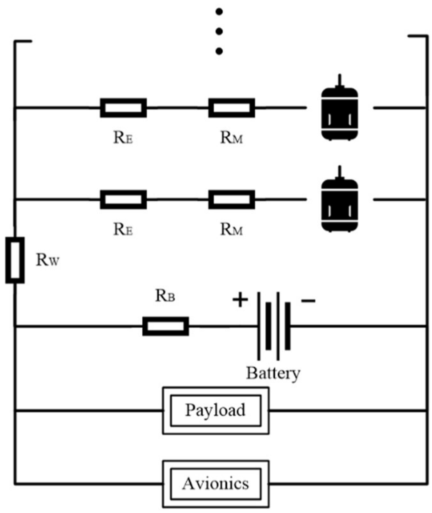


Fig. 9. Schematic of electric system

3 Results and Discussion

3.1 Validation of Analysis

Two multirotor UAV models were selected to validate accuracy of analysis method in CLOUDS. First model(model 1) was presented detail specifications of the components and flight conditions. Also, gross weight of model 1 was 4-kg and hovering time was shown in web site forum and reference [2] where its flight test video and data were existed. The model 1 consisted of components in Table 1. Second model(DevKopter) was manufactured and tested by KARI. Gross weight of DevKopter is 5.7kg and its specifications is shown in Table 2.

Table 1. Components of the model 1.

Component		Model 1 Specs	Model 1 Product name
Rotor	Diameter [inch]	28	Tiger Motor
	Pitch [inch]	9.2	
Motor	Speed Const. [Kv]	100	Tiger Motor U8
Battery	Capacity [Ah]	24	GEB8043125
	Cell	6	
ESC	Max Ampere [A]	30	Hobbywing

Table 2. Components of DevKopter

Component		DevKopter Specs	DevKopter Product name
Rotor	Diameter [inch]	18	Tiger Motor
	Pitch [inch]	6.1	
Motor	Speed Const. [Kv]	420	Tiger Motor U7 2.0
Battery	Capacity [Ah]	16	Volt-on
	Cell	6	
ESC	Max Ampere [A]	60	

With inputs of specifications and flight conditions, flight time analysis error of model 1 was 9.9% and the error of model 2 was 6.9% as shown in Fig. 10. The errors were acceptable in conceptual and preliminary design level, and established method in CLOUDS had reliable accuracy of performance analysis.

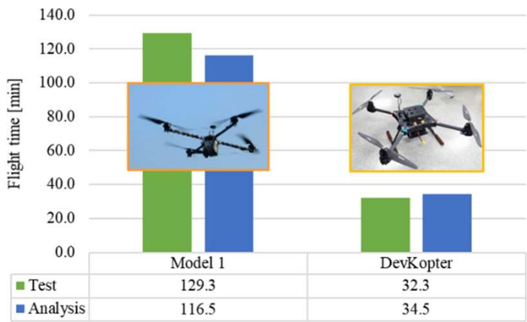


Fig. 10. Analysis results of CLOUDS

3.2 Optimized Designs

To design core components of multirotor UAVs, 12 design variables were chosen including parameters of the linearized propeller blade as shown in Appendix B. In addition, it was defined for feasible design that maximum battery discharge rate was 80% of total its capacity. Avionics current was 0.5-ampere and wiring weight was 50-gram, referred to Ref. [2]. Frame weight was the ratio of the total weight of other components and this ratio was based on the frame weight ratio value of a baseline.

Design problems were to optimize the components for objectives and a constraint:

- Objective 1: maximize hovering time.
- Objective 2: maximize range in forward flight.

Both problems had constraints that the optimized multirotor UAV had lighter gross weight than baseline's, and throttle range was 30%~50% for the feasible operation.
The baseline, DevKopter, could hover up to 31-minute or fly forward up to 34.5-km range with 17-m/s speed of advance, analyzed by CLOUDS. Optimization results are listed in Table 3.

Table 3. Optimization results

Design variable	Base line	Maximizing hovering time	Maximizing range
Rotor diameter (in)	18	31	14
Rotor pitch (in)	6.1	4.8	3.3
Motor speed constant (Kv)	420	356	680
Battery cell	6	4	6
Battery capacity (Ah)	16	21	16
ESC maximum ampere (A)	60	20	20

In hovering time maximization problem, the optimized design was that gross weight was 5.6-kg and hovering time was 40-minute, 29% longer than hovering time of baseline. The diameter of propellers was increased causing low RPM and mechanical power with increased torque at same thrust. Such aerodynamic advantage resulted in lower electrical power and drive current of motors. However, the diameter could not be increased more. In terms of electric system, the speed constant of motors was decreased for handling the increased torque. As a result, weight of motors was increased as shown in Fig. 11. The trade-off relation between diameter and the speed constant for hovering time was shown in Fig. 12. Due to the constraints of gross weight and operation throttle, optimum combination to the diameter of propellers and speed constant of motors was deduced.

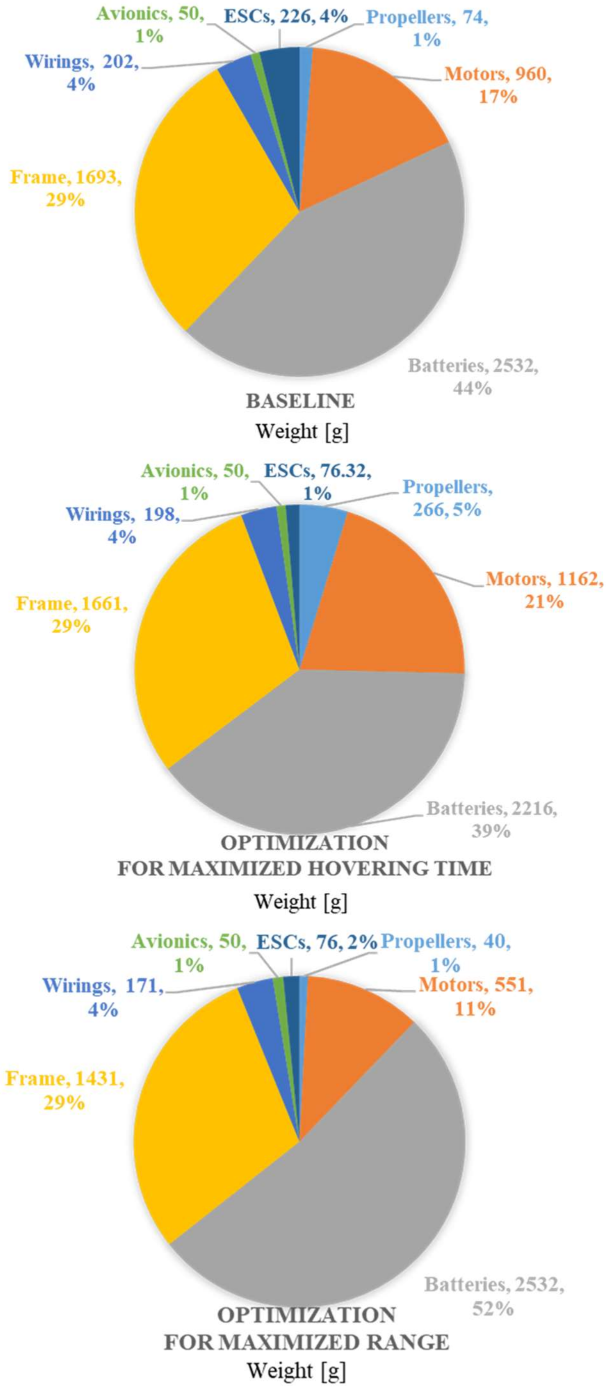


Fig. 11. Weights of components

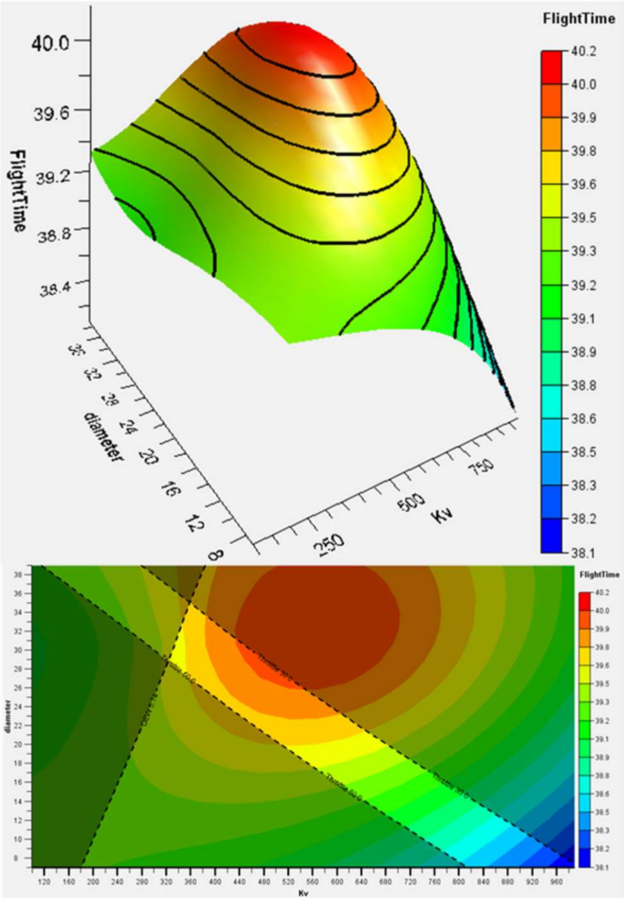


Fig. 12. Trade-off relation to hovering time

In range maximization problem, the optimized design was that gross weight was 4.5-kg, 21 lighter than the weight of baseline. Range was 46.7km, 35% longer than the range of baseline. Optimized diameter size was decreased in contrast with the hovering time maximization. Such optimized solution resulted from high rotating speed of propellers. In the forward flight, pitch angle and frame drag of the multirotor UAV require more thrust than hovering flight. As a result, the speed constant of motors was increased and diameter of propellers was decreased for low torque. It was shown in Fig. 13 that speed of advance of the multirotor UAV was increased as the propeller diameter was decreased.

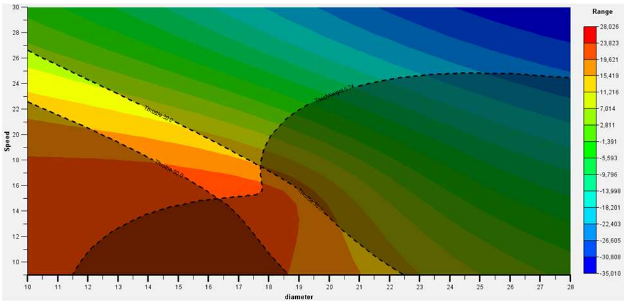


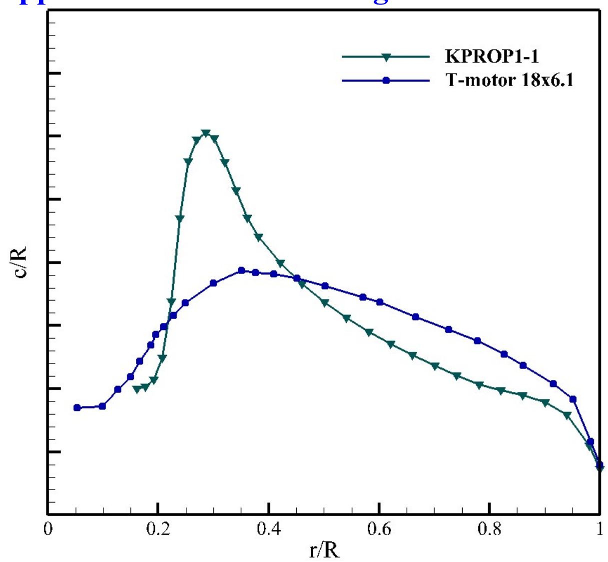
Fig. 13. Trade-off relation to range

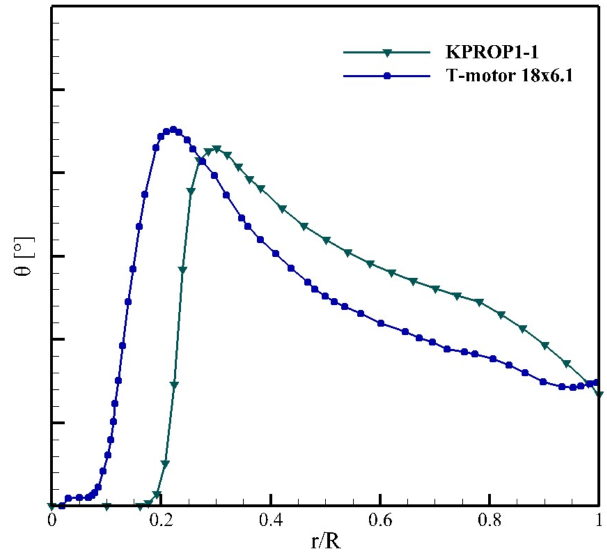
4 Conclusions

Based on multi-disciplinary analysis, systematic design procedure for multirotor UAVs was established in this paper. Aerodynamics of propeller, electric system analysis of motor and battery, and structure analysis of frame were reflected in the procedure. As a result, the analysis method of the procedure was validated with reliable accuracy for conceptual and preliminary design level.

As the principle flight type of various missions, multirotor UAVs were optimized in hovering and forward flight. Optimized design result for hovering time was accomplished by increased propeller diameter causing decreased rotating speed and mechanical power based on the aerodynamic advantage. However, lower rotating speed caused higher torque at same required thrust. As a result, speed constant of motors was lower and weight of motors was increased. On the other hand, the decreased diameter was optimized for the range maximization. Because the rotating speed of propellers should be increased for the forward flight, speed constant of motors was lower and their weight was lighter. Such trade-off relationship between propeller diameter and motor weight was the key to investigate the optimum design solution. Optimized set of the propellers, motors and battery could be more proper to a specific mission, even if usable electrical power of a battery became low and weight portions of propellers and motors to gross weight increased. For this reason, propeller and motor should be designed concurrently based on multi-disciplinary analysis.

Appendix A. KPROP Configuration





Appendix B. KPROP Configuration

Group	Design variable		Description
Rotor	Diameter		Rotor diameter
	Chord	c_{root}	Chord length at root cut-out
		r_{Cmax}	Position at maximum chord
		C_{max}	Maximum chord length
		C_{tip}	Tip chord length
		$r_{\theta max}$	Position at maximum twist
		θ_{max}	Maximum twist angle
		θ_{tip}	Tip twist angle
Motor	Speed constant		Motor speed constant
Battery	Capacity		Battery capacity
	Number of cells		Number of cells in the battery
ESC	Maximum ampere		Maximum ampere of ESC

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