Design Process of an Autonomous Modular UAV (Hükümdar)

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Abstract- **This study deals with the design, manufacturing and testing processes used by Turkish Air Force Academy Hükümdar Team in preparation for the FFD 2013 Future/Flight/Design Competition. The goal of the competition is to design and build an unmanned, electric powered, radio controlled aircraft by maximizing total score, which is a function of report and flight score.**

I. Introduction

In recent years, Unmanned Air Vehicles have been widely used in military industry, because of their low-rate costs and effectiveness. The goal of the competition is to design and build an unmanned, electric powered, radio controlled aircraft by maximizing total score, which is a function of report and flight score. This study details the design, manufacturing and testing processes used by Turkish Air Force Academy Hükümdar Team in preparation for the FFD 2013 Future/Flight/Design Competition.

II. Mission Requirements

The total score is directly affected by the written report and the total flight score. The total flight score is the sum of the individual mission flight scores.

Flight score (FS) is determined by performance in three payload flight missions. In one of the payload missions, the aircraft will carry a 500 ml water bottle; in the other payload mission, it will carry 500 ml four water bottles after a compulsory modification on the aircraft. The aircraft must have a high speed and low total system weight in the First Mission, easy loading in the Second Mission, a high speed and it should make three successful 500 ml water bottle drops in the Third Mission. Takeoff should be hand-launch and hand-launch distance (10 meters) are limited by the contest rules. A score analysis on FS reveals Total aircraft weight and flight velocity as the most critical design parameters. Contest specified mission and vehicle requirements are as follows:

- NiCad,NiMH and LiPo batteries are allowable to use.
- 40 Amp (blow fuse) current limit.
- Maximum takeoff by hand-launch distance is 10 meters .
- Water bottles must be carried internal to the aircraft.
- The aircraft must complete a successful landing at the end of a mission for the mission to receive a score.
- No structure/components may be dropped from the aerial vehicle during flight (except mission requirements).

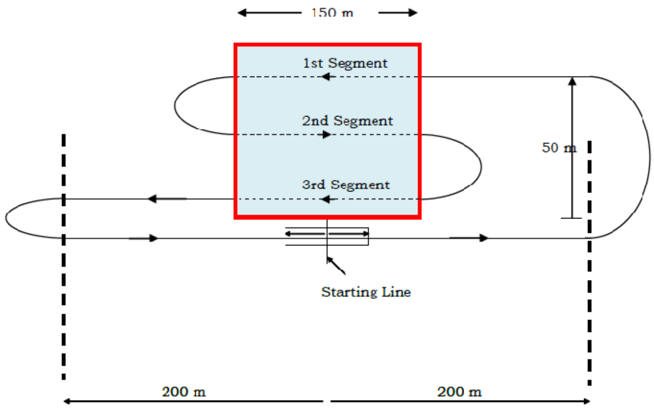

Fig. 1. Flight Pattern (dimensions in meters).

A. Mission 1: A flight with 1-bottle payload

The mission is flown with one 500 ml water bottle payload. Flight time starts with the hand-launch and ends with a flyover finish after the completion of two laps of the flight course. The aircraft must land on the runway to receive a score.

B. Mission 2: One lap payload flight

The mission is flown with four 500 ml water bottle payload. At this mission,it is necessary to use a UAV is modified for the specified mission.Loading time of the bottles is important.

Time will begin with the aerial vehicle on the start/finish line and time will end when mission is completed.

And the aircraft flies one lap of the flight course with the payload. Aircraft must land on the runway to receive a score.

C. Mission 3: Three lap payload flight

At this mission the payloads are three 500 ml water bottles.

It includes a flight with 3-bottle payload to the target area and dropping them in order (in each flight segment) inside the target area. Payload have to be landed with a parachute. A successful landing means no leakage on the bottle. Loading of the bottles is not timed.

Flight time is from start of take-off (hand launch) to completion of the lap.

The third lap is completed when the aircraft passes over the start line while stil in the air. The total score is the outcome of the report score ,volume score of the box which is used for carrying the aircraft and the flight score. The flight score includes three components calculated after each completed mission.And it multiplies in respect to type of aircraft.

TS = (0,5*Report Score 0,5*Volume Score *1,0 Flight Score) *Modularity Factor

For Modified UAV
FS = 0,5*(T_1*W_1*100+T_2*W_2*150+T_3*N_bottles*75)

For Original UAV
FS = 1,0*(T_1*W_1*100+T_2*W_2*150+T_3*N_bottles*75)

For Autonomous UAV
FS = 2,0*(T_1*W_1*100+T_2*W_2*150+T_3*N_bottles*75)

Modularity Factor is a multiplier and computed using the formula;

$$\text{MODULARITY FACTOR} = \frac{(w_2 - w_{12}) \times dw}{{w_2}^4 + w_{12}}$$

where,
w_2: Maximum empty weight of an aircraft for mission 2 and 3.
W_{12}: The weight of modular parts added to base aircraft.
dw: The difference between empty weight of base aircraft and .

III. Conceptual Design Selection Process

After evaluating all the competition rules and our score analyses for the missions, we determined the competitive design requirements as follows:

TABLE I
AIRCRAFT CONFIGURATION DECISION MATRIX

TEAM OF HÜKÜMDAR				
FIGURE OF MERIT	Weight Factor	Conventional	Bi-Plane	Canard
Convenience	30	1	0	-1
Drag	25	0	-1	1
CG Balancing	30	1	0	0
Storage Size	15	1	0	-1
TOTAL	100	75	-25	-20

TABLE II
EMPENNAGE CONFIGURATION DECISION MATRIX

TEAM OF HÜKÜMDAR					
FIGURE OF MERIT	Weight Factor	Cruciform	Conventional	T-Tail	V-Tail
Stability & Control	30	1	1	1	0
Weight	25	-1	0	-1	1
Drag	15	0	-1	1	1
Manufacturing	20	-1	1	-1	0
TOTAL	100	-15	35	0	40

TABLE III
LANDING GEAR CONFIGURATION DECISION MATRIX

TEAM OF HÜKÜMDAR				
FIGURE OF MERIT	Weight Factor	Tricycle	Bicycle	Tail-Dragger
System Weight	30	0	1	1
Safety of Empennage	20	1	1	-1
Drag	10	-1	0	0
Ground Handling	50	1	0	0
TOTAL	100	60	50	10

TABLE IV
PROPELLER LOCATION DECISION MATRIX

TEAM OF HÜKÜMDAR				
FIGURE OF MERIT	Weight Factor	Single Pusher	Single Tractor	Double Tractor
RAC	35	0	0	0
Manufacturing	25	1	1	0
Efficiency	10	0	-1	-1
Stabiliy & Control	20	0	0	1
Drag	15	20	10	30
TOTAL	100	20	10	30

TABLE V
WING PLACEMENT DECISION MATRIX

TEAM OF HÜKÜMDAR				
FIGURE OF MERIT	Weight Factor	Low	Mid	High
Load. & Rel. Cap.	35	0	0	0
Stability & Control	25	0	1	1
Drag	10	-1	0	-1
RAC	20	1	0	0
Velocity & Lift	15	30	20	10
TOTAL	100	30	20	10

Final conceptual design has a high-wing conventional configuration with tricycle landing gear. It has a boom-mounted conventional, a single tractor propeller and a single-single (single motor-single batterypack) propulsion system.

III. Preliminary Design

After finishing the conceptual design, the team started working for the preliminary design by combining a flowchart. After that, we make the initial sizing, aerodynamic, mechanic, propulsive and structural characteristics of our winning aircraft. Before sizing and optimizing the aircraft, we decide the critical design parameters which will have a great impact on the performance and scoring.

A. Optimization Methodology

The optimization methodology includes stability and control, aerodynamics, propulsion, structure and performance modules.

- *Aerodynamics:* In this module, we calculate the lift and drag coefficients, Reynolds number and aerodynamic forces using Design Foil Program. We use altitude-corrected air density and temperature of Wichita, Kansas for our aerodynamic performance predictions assuming no wind.

- *S&C:* The stability and control module includes static and dynamic stability analyses. We calculate the static margin and the S&C derivatives. After that, we size the control surfaces.

- *Propulsion:* In this module, we look for the best motor, propeller, gearbox, and battery combination that meets our mission requirements. We use DBF database for the selection parameters. We calculate thrust, voltage, current and efficiency of the system and choose the best.

- *Structure:* In this module, we calculate the deflection, normal and shear stress of the wing, fuselage and tail boom and the loads on the landing gears by using Catia V5R19 Program.

- *Performance:* In this module, take-off distance, mission times, total system weight, cruise speed, required energy, turn radius and throttle settings are calculated.

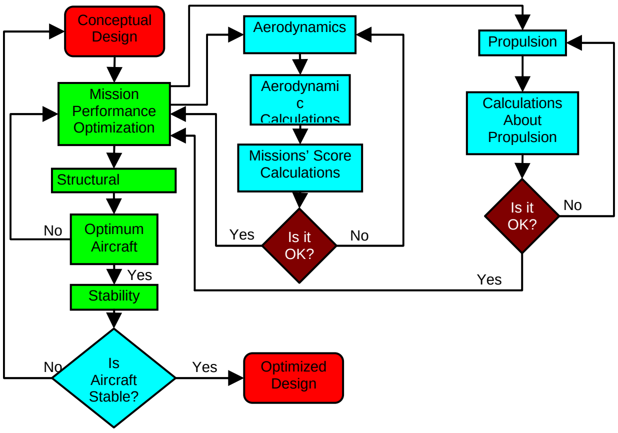

Fig. 2. Aircraft Optimization Flowchart.

B. Airfoil Optimization

Airfoils taken into consideration to choose one for our aircraft are shown below.

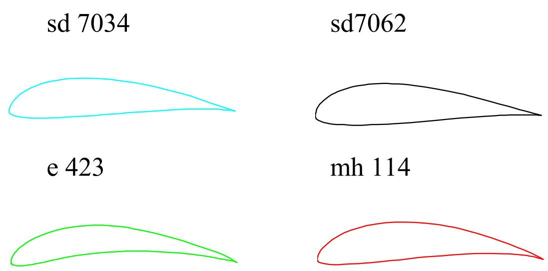

Figure 3. Considered airfoils for the aircraft.

Some analyses are done in order to select the best airfoil. While analysing the airfoils, our observations are small drag, convenient moment and high lift values. High lift is required because we need short take-off distance, especially with payloads. But high lift airfoils generally tend to create more drag. So, our analysis objective is to find the best airfoil which has high lift, low drag and good moment features together. First of all, we compared the drag polars of each airfoil.

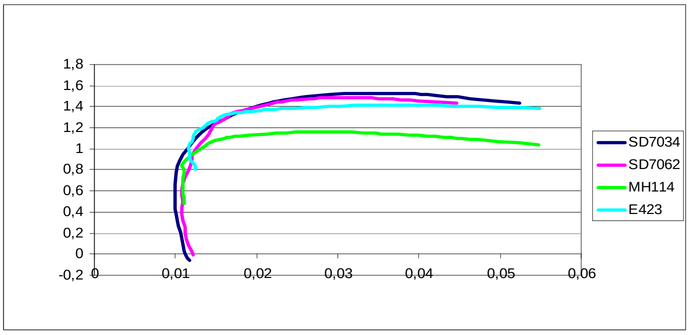

Figure 4. Cl-Cd Graph of Airfoils.

When we look at the Cl-Cd graph, it can be understood that sd7034 and e423 profiles have the best finess and only separated by a little margin from each other.

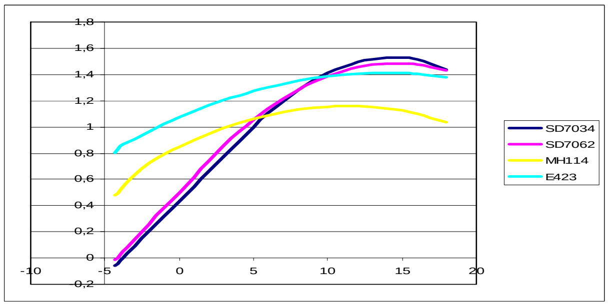

Figure 5. Cl-AOA Graph of Airfoils

When we look at the Cl-AOA graph, sd7034 and sd7062 have the best and almost the same Cl_{max} values while e423 and Mh114 values are considerably bad. Although e423 and Mh114 have better Cl values for small angles, their Cl_{max} values are not as good as the others.

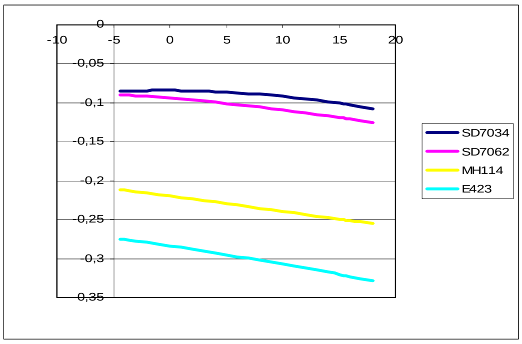

Figure 6. Cm-AOA graph of Airfoils

In the Cm-AOA graph, we want negative slope curve and since the aircraft Cm0 must be positive, the Cm0 value of the curve must be closest to the positive values. So, sd7034 has the best Cm-AOA curve.

As a result, evaluating the finess, Cl-AOA and Cm-AOA graphs, we choose sd7034 airfoil for our aircraft. Because it has the best values among the other airfoils. Another reason for choosing this airfoil is that sd7034 is known as a low-drag airfoil, because, especially in the Mission 3, the aircraft would have high drag values due to the bats, so we need to choose a low drag airfoil for that.

C. Wing Geometry

In order to determine the wing geometry, we use some graphs showing different airfoils wing area-score and wing span-score values. Although we choose sd7034 as our airfoil, we also take the other airfoils into consideration to see whether our choice is the best or not.

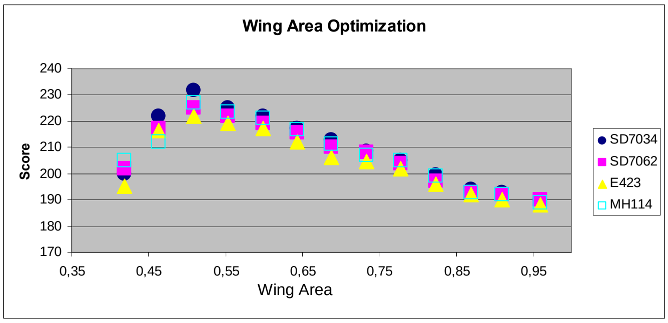

Figure 7. Score-wing area graph of airfoils

As seen in the graph, sd7034 airfoil has the best values. While determining the wing area, we need to consider both the take-off distance limit and the maximum score together. After this analysis, the wing area is chosen as 0,52 m^2. Our aircraft's minimum weight will be aproximately 5 kg for first mission. Because of this, we've decided that wing area should be 0,5237 m_2 area. When we add extra payloads in second and third missions, our aircraft's maximum weight will increase to approximately 6,7 kg. In order to supply ample lift for these missions, the new wing area will be risen up to 0,6152 m^2.

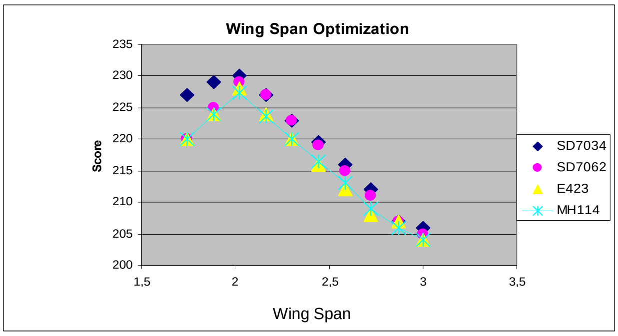

Figure 8. Score-wing span graph of airfoils

After the wing area is determined, we make an analysis to select the wing span. Again, SD7034 has the best values, which proved that our choice is correct. While determinig the wing span, the limitations are the box size and the maximum score. As a result, wing span is chosen as 1,92 m.

D. Fuselage

The shape and size of the fuselage was decided considering the selected payload configuration and drag characteristics. The nose was sized to fit the propulsion system and the aft portion of the fuselage was sized to create a total fuselage length of 87 cm in order to reduce control surface areas.

D. Empennage

After deciding the type of the empennage, firstly we defined the boom length according to the moment calculations and box sizing. After that, we sized our conventional tail by using the formulas shown below from Raymer.

$$c_{VT} = \frac{L_{VT}S_{VT}}{b_W S_W}$$

$$c_{HT} = \frac{L_{HT}S_{HT}}{\bar{C}_W S_W}$$

C_{VT} and C_{HT} values are taken from historical data table from Raymer. S_w, b_w and C_w values are already determined in the previous sections. After that, by using the equations above, L_{VT}-S_{VT} and L_{HT}-S_{HT} values are determined after optimization to ensure the stability of our aircraft.

E. Stability&Control Analysis

The calculation of stability and control can affect response of the aircraft against undesirable moments. The process for achieving static stability for our aircraft configuration required to refine a center of gravity model and update a stability spreadsheet that provided the necessary calculations and graphs for both static and dynamic stability.

In third mission, our airplane has to carry three water bottles. It throws bottles one by one. After throwing each bottle, a strong possibility occurs that center of gravity changes. For changing of center of gravity could result in loss of control of the aircraft, we have decided that center of gravity must be kept fixed. Firstly we settled center of gravity of the airplane and the mechanism of bottles at same point. Secondly, aerodynamic center of wing was positioned on point of center of gravity. Upon this, despite the fact that our airplane throws bottles, the center of gravity doesn't change anymore. We decided on not to change the position of the batteries for each mission in order to keep the center of gravity constant throughout all missions.

Initial stability and control analysis were performed to ensure a statically stable aircraft and an acceptable static margin. At the beginning, we placed the batteries and the electronic speed controller ahead of the fuselage, somewhere near the motor. And, stability and control calculations have showed us that this placement makes it alright to control the aircraft and makes aircraft dynamically stable. So, we have decided to place them in front of the fuselage.

$$\bar{X}_{np} = \frac{C_{L_\alpha}\bar{X}_{ac_{wing}} - C_{m_{\alpha\,fuselage}} + \eta_{HT}\frac{S_{HT}}{S_{wing}}C_{L_{\alpha\,HT}}\frac{\partial\alpha_{HT}}{\partial\alpha}\bar{X}_{ac_{HT}} + \frac{F_{P_a}}{qS_{wing}}\frac{\partial\alpha_P}{\partial\alpha}\bar{X}_p}{C_{L_\alpha} + \eta_{HT}\frac{S_{HT}}{S_{wing}}C_{L_{\alpha\,HT}}\frac{\partial\alpha_{HT}}{\partial\alpha} + \frac{F_{P_a}}{qS_{wing}}}$$

In order to calculate aircraft static margin using equations, cruise flight stability values were examined for all missions.

$$(\bar{X}_{np} - \bar{X}_{cg}) = -\frac{C_{m_\alpha}}{C_{L_\alpha}}$$

The above equations is used to calculate the value of static margin.

Factor	Mission 1	Mission 2	Mission 3
Static margin	24,92%	28,04%	28,04%
Cm_α	-1,11396	-1,36591	-1,36591

Figure 9. Static Margin Values Found for the Missions

After the static stability analysis, we made the dynamic stability analysis which demonstrates the aircraft's ability to fly straight, do necessary maneuvers and not to be affected by torque of mechanism while next bottle is replacing the other one in third mission. Stability derivatives for the dynamic stability calculations were found by using methods from Nelson and Raymer. We used two different wings in order to increase MF. So there are two values in chart because of modification in assessing wings. Sizing wing can change stability and control derivative coefficients

TABLE VII
STABILITY AND CONTROL DERIVATIVE COEFFICIENTS

Stability and Control Derivative Coefficients											
$C_{L,\alpha}$	4,4694	4,8705	$C_{n,\beta}$	0,0748	0,0504	$C_{y,r}$	0,152	0,103	$C_{M,\alpha}$	-1,293	-1,366
$C_{l,\delta a}$	0,547	0,466	$C_{n,\delta a}$	-0,012	-0,004	$C_{y,p}$	0,0289	0,0341	$C_{M,\delta e}$	-1,5625	-1,4006
$C_{l,\beta}$	-0,0002	-0,0002	$C_{n,\delta r}$	0,0174	0,0118	$C_{y,\delta r}$	0,366	0,247	$C_{M,q}$	-17,61	-12,81
$C_{L,\delta e}$	0,109	0,069	$C_{n,r}$	-0,226	-0,145	$C_{y,\beta}$	-0,444	-0,377			
$C_{l,\delta r}$	0,253	0,161	$C_{n,p}$	0,0338	0,0362						
$C_{l,p}$	-0,825	-0,941									
$C_{l,r}$	1,153	1,152									

F. Control Surface Sizing

The control surfaces were sized using previous aircrafts as a benchmark, with general sizing for a number of aircrafts being considered. Since we have a V-tail, there is only one control surface which does the same actions of rudder and elevator together. That surface which we called ruddervator has a size of 30% of the horizontal tail area and a ±20° maximum deflection.

The ailerons were sized using Raymer to provide enough roll control during turning and take-off. The ailerons were sized to a total area of 17% wing area with +20°/ -10° maximum deflections.

G. Propulsion Analysis

Motor has to reach some limits in order to obtain required thrust and power. Because a motor, which has insufficient thrust, cannot overcome drag forces. So, we firstly obtained thrust and power values from Prop Selector Programme. We indicated some values such as airspeed, RPM, number of prop blades, balde pitch and popr diameter. Then we acquired thrust, power output, power absorbed and efficiency values as shown in program in Figure 10.

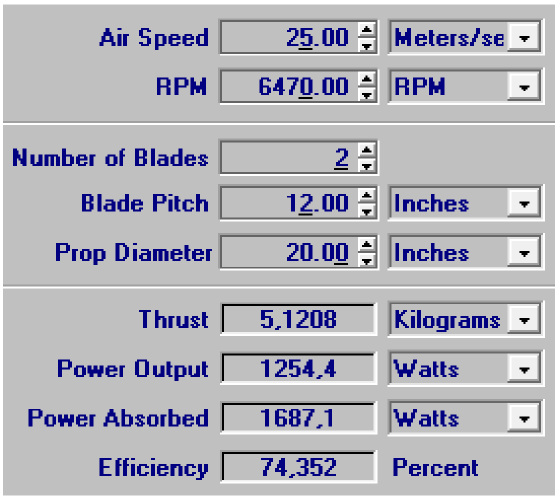

Figure 10.Output Values from Prop Selector Programme

After this process, thrust value must be compared with drag forces. . Drag forces were calculated according to Mission 3, for this mission includes some troublesome conditions about drag force.

D= 0,5.1,2256.252.0,9171.0,0296 = 10,39 N

$D = T_{required}$

$P_{required}$ = T.V / e = 10,39.25 / 0,74= 351 W (Minimum power value for cruise.)

T= 5,1 kg =50 N

$T > T_{required}$

P= 1254 W

$P > P_{required}$

TABLE VIII
FINAL DIMENSIONS OF THE DESIGN

WING (MISSION 1)		AILERON			
Span [cm]	192	Span [cm]	52,5		
Root Chord [cm]	31	Max Chord [cm]	6	HORIZONTAL STABILIZER	
Tip Chord [cm]	20	Min Chord [cm]	4,5	Span [cm]	72
Aspect Ratio	7,04	ELEVATOR		Root Chord [cm]	22
Airfoil	SD7034	Span [cm]	72	Tip Chord [cm]	16
Static Margin	20%	Max Chord [cm]	10	Airfoil	NACA 0009
Wing Area [m^2]	0,5237	Min Chord [cm]	8	Wing Area [m^2]	0,27
WING (MISSION 2)		RUDDER		Incidence	0
Span [cm]	242	Span [cm]	35	VERTICAL STABILIZER	
Root Chord [cm]	31	Max Chord [cm]	6	Span [cm]	35
Tip Chord [cm]	18	Min Chord [cm]	5	Root Chord [cm]	18
Aspect Ratio	9,52	BATTERIES		Tip Chord [cm]	12,5
Airfoil	SD7034	Type	Li Po 7s 2p	Airfoil	NACA 0009
Static Margin	20%	Capacity	1900mah	Wing Area [m^2]	0,13
Wing Area [m^2]	0,6152	R	1,56	PROPELLER	
FUSELAGE		V	7X4 V	Pitch [inch]	20
Length [cm]	87	Wire	22 ga	Pitch [inch]	12
Width [cm]	22	Number of Cells	14	Model	APC
Height [cm]	17	Pack Capacity [gr]	640		
GTOW (est.) [gr]	785	Rl	0,0156		
ELECTRICAL SYSTEM	Speed Controller		Phoenix Ice HV40		
	Radio Receiver		Futuba R6014 HS		
	Number of Servos		9		
	Types		Hitec HS-125MG servo (6)		
			Hitec HS-825 servo (3)		
MOTOR	Thrust [kg]	5,1	Type	Hacker C50-14 XL Acro	
	Weight [gr]	423			
	Kv	1740	Shaft d. [mm]	8	
	Rl	0,0156	Gear Ratio	6,7:1	
	Propeller	20x12	Idle Current [A]	1,3	

IV. CONCLUSION

After the preliminary design is completed, we concentrated on the detail design phase. During detail design, all systems and components are selected and integrated. The aircraft structural characteristics and capabilities are finalized, and a complete aircraft sizing is expanded into a CAD loft depicting all features and dimensions. A weight and balance summary is compiled for each mission, including different payload combinations. Finally, flight and mission performance parameters are documented.

The table below shows the final lengths, widths, and diameters of the fuselage, tail, and wing in addition to other important aircraft parameters.

ACKNOWLEDGMENT

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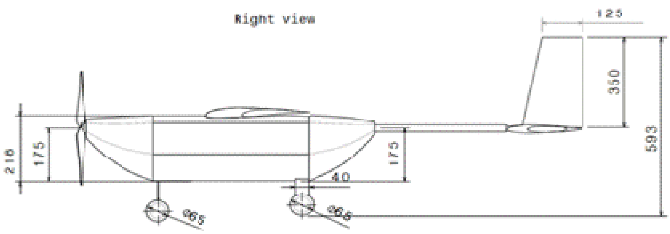

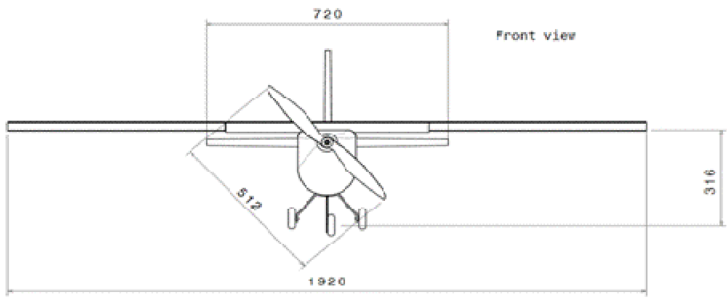

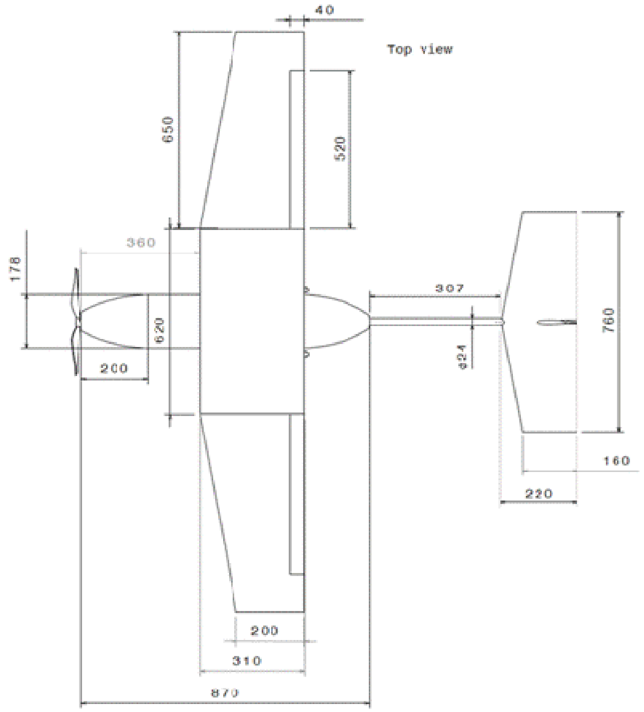

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REPORT TITLE : DRAWING PACKAGE	DRAWING NO : 2013 - 001	
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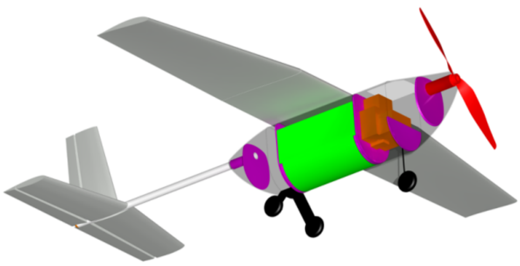

COLOR	ITEM
Red	Power Plant
Magenta	Structural Components
Green	Payloads
Black	Landing Gears
Orange	Electronics
White	Wing and Tails

TURKISH AIR FORCE ACADEMY		
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REPORT TITLE : COLORED SCHEME	DRAWING NO : 2013 - 002	
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