Optimization of Design and Control of Micro Air Vehicle for EMAV-09 Indoor Dynamic Competition

S.V. Serokhvostov
Moscow Institute of Physics and Technology, Department of Aeromechanics and Flight Engineering, 16 Gagarina street, Zhukovsky, Russia
T.E. Churkina
Moscow Aviation Institute, Volokolamskoe shosse 4, Moscow, Russia

ABSTRACT

Considered is optimization of aircraft performance and trajectory for EMAV-09 indoor dynamics competition to obtain the maximal score for the fixed level of autonomy. Mathematical model was formed and analyzed. Maximal scores and corresponding performance and trajectories are found for given values of initial parameters (mass of electronic devices, accumulator and drive characteristics, viscous drag coefficient). Sensitivity of score function to the small changes in initial characteristics and the behavior of the score function near the maximum are investigated. Results obtained were validated on the test models.

1 INTRODUCTION

One of the competitions of EMAV-09 (and previous European MAV competitions) is the indoor dynamics competition, which includes flying along the figure "8" around two poles, time of flight being fixed. The score is calculated on the basis of the maximal dimension of MAV, the level of autonomy and the number of "8" figures made by MAV during the flight. If the aircraft has flown over the pole, then the corresponding "8" figure is not taken into account [1].

This investigation has the aim to determine the trajectory and characteristics of MAV that can provide the maximal score for this competition for the fixed level of autonomy.

Assume that one can choose the velocity of flight, wing area, trajectory, mass of accumulators etc. for the maximization of score for the fixed values of "unchangeable" components mass and wing aspect ratio λ.

2 MODEL

According to the rules of EMAV-09 indoor dynamic competition [1], the distance between the poles is L_0=10 meters, their heights are 4 meters. It is assumed that the mean velocity of flight is high enough for these distances (about V=5 m/s or more). Such assumption can be made on the basis of the previous competitions results [2]. The winner of the EMAV-08 indoor competition ("Hummingbird" from "DLR/Ascending Technologies" controlled by the pilot) have made 23 figures of "8". Assuming that the trajectory was consisted of two circles of 5 meters diameter (L/2), one can obtain that the mean velocity is about 4 m/s. In real case the velocity must be higher as the trajectory is not so "perfect". At these velocities the angles of trajectory inclination must be rather low to avoid the accidental climb over the poles and accidental crash. This leads to the conclusion that the possible vertical velocities and altitude changes must be small enough. So, for the first approximation, the altitude must be considered as constant.

As the characteristic time L_0/V is about 2 seconds and the trajectory is assumed to be symmetrical, the aircraft cannot greatly change its velocity (the characteristic acceleration for the significant change is $V^2/(L_0/2)\approx 5\text{m/s}^2$ which assumes rather high additional thrust-to-weight ratio which leads to additional mass of aircraft). Also, the deceleration leads to the increase of time for one "8" figure and, as consequence, decrease of the number of figures during 3 minutes. So, the velocity can be assumed constant during the flight.

Also, the characteristics of autopilot (time delay) or operator and of onboard devices (servos and speed controller) give additional arguments for the assumption of velocity and altitude constancy during the flight.

In common case the aircraft flies along the curved line, so the centripetal acceleration must be taken into account. As the altitude is constant, then

$$(1)\qquad \left(C_L\rho\frac{V^2}{2}S\right)^2=\left(mg\right)^2+\left(\frac{mV^2}{R}\right)^2$$

where C_L – lift force coefficient, S – wing area, ρ – air density, m – mass of MAV, R - radius of curvature of the curve, g – acceleration of gravity. So, one can see that the trajectory strongly depends on the parameters of aircraft (S, m) and flight conditions (V, C_L).

The power W required for a certain moment of time is

$$(2)\qquad W=\left(C_{D0}+AC_L{}^2\right)\rho\frac{V^3}{2}S$$

where $A=2/(\pi\lambda)$ for low aspect ratio wings [3].

Total mass of aircraft can be roughly expressed as

$$(3)\qquad m=m_0+m_{acc}+m_{wing}+m_{drive},$$

where m_0 is the mass of "constant" components, which can not be changed during the optimization, m_{acc} is the mass of accumulator, m_{wing} is the mass of the wing, m_{drive} is the mass of electrical drive.

Email address: serokhvostov@mail.ru

In first approximation, the mass of drive is proportional to its maximal power. For small drives the ratio of Power/Mass is about 3 Watt/gram (see, for example, [4]).

The mass of the wing can be assumed to be proportional to its area, the proportionality coefficient depends on the material of the wing.

The mass of the accumulator depends on its capacity and maximal discharge current. During the first step of investigation it is important to determine what condition is dominating. (For long flight time with the low current the main characteristic is capacity, for the short flight with the high current the main characteristic is the maximal discharge current.) Traditionally, the capacity C of the accumulator is defined in Ampere·hours. In RC model sport community the maximal discharge current is expressed in "C". For example, for the accumulator with "10C" and the capacity of 1 A·h the maximal discharge current will be 10A.

Imagine that the accumulator with the capacity of Q Ampere·hours must work during the time of t hours. So, the mean current is Q/t Amperes. So, the minimal value of maximal discharge current must be $(1/t)$ of "C".

As the flight time for this competition is 3 min (1/20 hour), than for the accumulator with "20C" discharge current the requirements for capacity and current are equal (at the assumption that the current is constant during the flight). For the lower maximal values of the accumulator maximal discharge current the main characteristic is the discharge current, for the higher values the main characteristic is capacity.

As the small accumulators have the discharge current of about 10-15C, then we will analyze first of all the case of the accumulator mass determination through the maximal discharge current.

The energy consumed from the accumulator depends on the energy required for flight and efficiency of powerplant which depends on the thrust and flight velocity. As the flight velocity is assumed to be constant in our case then the efficiency is the function of thrust. It was shown in [5] that the efficiency changes rather slowly with thrust in working range. So, assume that the powerplant efficiency is constant.

3 TRAJECTORY AND PERFORMANCE OPTIMIZATION

Assume that the aircraft has the known values of S, m, m_{acc}, and one wants to maximize the score by choosing the optimal V and trajectory.

Number N of "8" depends on the length of trajectory s_1 of one figure "8" and velocity for the fixed time T:

$$N=VT/s_1.$$

So, for the certain V the value of s_1 must be minimal of all the possible variants.

It is well known that the shortest trajectory between two points is straight line. But in our case the trajectory is closed "curve" and it cannot consists only of two lines, as for any value of velocity the acceleration in the extreme points will be equal to infinity. So the trajectory must also have the curved parts. Besides, the higher the value of radius of curvature of the curve, the higher the value of s_1. So, for the curved parts of trajectory the value of R must be minimal (i.e. constant). The curve with constant R is the part of circle.

So, one can make the conclusion that in our case the optimal trajectory will consist of two parts of circles and two straight lines (Figure1).

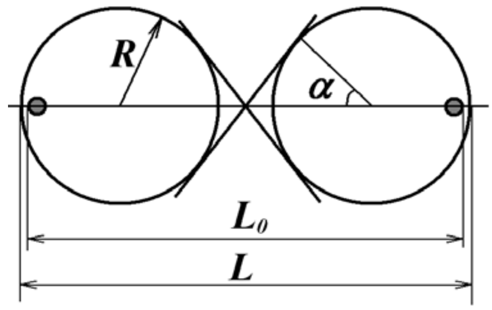

Figure 1: Optimal trajectory.

For the minimization of s_1 it is required that the trajectory must be as close to the poles as possible. The minimal distance between the trajectory and pole is defined by the MAV construction parameters, pilot's level of skill or autopilot characteristics. But for this investigation it is assumed that this distance $(L-L_0)/2$ is known (see Figure 1).

Then, value of s_1 can be expressed as

$$(4)\quad s_1 = 2\left(R\left(2\pi-\alpha\right)+2\sqrt{\left(L-R\right)^2-R^2}\right),$$

where

$$(5)\quad \alpha = arccos\left(\frac{R}{L-R}\right).$$

For fixed value of V and m_{acc} (i.e. maximal W) the minimal value or R is fixed and defined through the values of maximal W and values of S, V, m, g, ρ, C_{D0} (see (1) и (2)).

The optimized function is *Score* Φ [1]

$$(6)\quad \Phi = N\left(2-\frac{L_{wing}}{L_{max}}\right)^3 = \frac{TV}{s_1}\left(2-\frac{L_{wing}}{L_{max}}\right)^3,$$

where L_{wing} is wingspan, L_{max} – maximal allowed wingspan.

As the aspect ratio is fixed, then L_{wing} can be found from S.

With the help of equations (1)-(5) the maximal value of Φ as the function of V, m_{acc}, l_{wing} can be found.

It is rather evident that it is practically impossible to solve this problem analytically. So, the numerical analysis was carried out. The velocity V for the fixed m_0 was searched as function of S, R and m, and then the *Score* Φ was calculated. Varying S, R and m the maxima of Φ for given values of m_0 were found.

For the simplicity of the analysis it was assumed that $L=L_0$=10m. Also, it was considered that the power density of accumulator is 100 W/kg, square density of the wing is 0,1 kg/m^2.

4 RESULTS AND DISCUSSION

In Table 1 one can see the results of MAV optimization for a set of m_0 values.

These results give the information for several conclusions. First of all, the radius of the circle parts remains constant with enough accuracy for the wide range of m_0 values. Also, it is close enough to its maximal value of $L/2$=5m. So, for the simplicity one can assume the trajectory as two circles with $R=L/2$.

Second, the value of velocity varies rather slowly with the m_0 changes, so it can also be assumed to be constant for the further investigations.

m_0, kg	0,025	0,03	0,035	0,04
l_{wing}, m	0,246	0,255	0,262	0,269
S, m^2	0,048	0,052	0,055	0,058
m, kg	0,064	0,073	0,085	0,095
$2R$, m	4,56	4,56	4,56	4,55
V, m/s	11.8	11,7	11,3	11
m_{acc}, kg	0,034	0,039	0,045	0,046
C_L	0,1	0,12	0,177	0,2
m_{acc}/m	0.53	0.53	0.53	0.52
Score Φ	490	468	449	433

Table 1: results of the optimization.

Third, the value of C_L is much smaller than its maximal value, so there will be no effects of flow separation and stall.

Fourth, the ratio m_{acc}/m is practically constant for a wide range of m_0. From one side, it allows to use this result for other values of m_0. From other side, it looks like "fundamental regularity" and requires the additional investigation.

Figures 2-4 illustrate the data from Table 1. It can be seen that the graphs are rather close to the straight lines. It can make the design process for other values of m_0 simpler. But for the more thorough investigations one must keep in mind that the second derivative of these graphs can be small but not equal to zero.

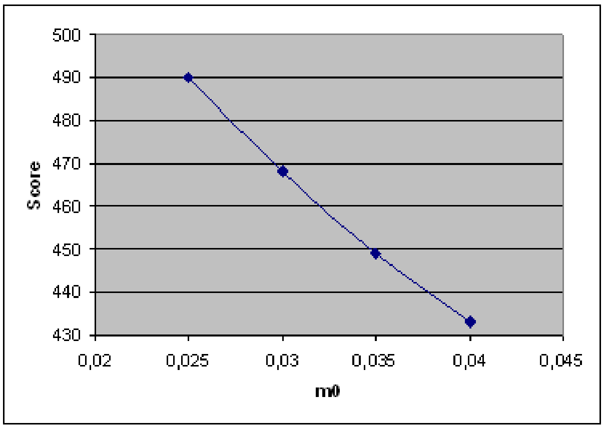

Figure 2: Score vs. m_0 for optimal design.

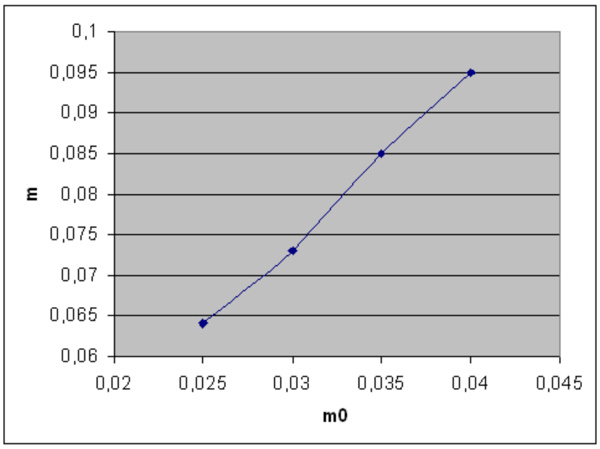

Figure 3: Total mass vs. m_0 for optimal design.

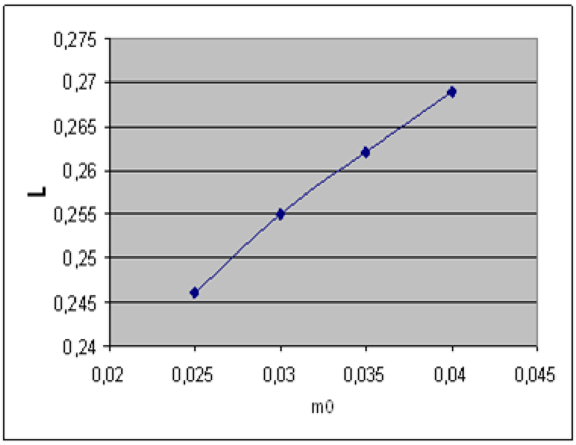

Figure 4: Wing span vs. m_0 for optimal design.

The optimal velocity is higher that is assumed above. So, arguments for the constancy of the altitude and the velocity based on this value were valid. Also, as the trajectory consists mainly of the circles of equivalent radius, the thrust during the flight remains mainly the same. So, the thrust is mainly the same and the assumption about the constancy of powerplant efficiency is also valid.

For V and R obtained the characteristic time for one figure of "8" is about 3 seconds. First of all, it leads to the conclusion that it is very difficult to control the aircraft manually. So it needs a pilot with very high qualification or some kind of autopilot. Also, even with autopilot it is rather difficult to fly precisely along the predefined path especially for the complex trajectory. From this, the above assumption about the trajectory consisted of two circles is valid and can be recommended for this velocity.

It is rather evident that it is impossible to guarantee the availability of the accumulators with the required mass. Also, as it was shown above, it is difficult to fly precisely along the predefined trajectory. At last, it is difficult to make the MAV with the predefined geometry. So, it is important to know the behavior of function Φ near its maximum.

Figure 5 shows the behavior of Φ for S=0,052m^2 and m_0=0.03 kg (R and m_{acc} can be varied, m is function of m_{acc}).

Five points of *Score* for these conditions correspond to one figure of "8". The area where the difference with respect to maximal score is less than 5 points is marked red. As can be seen that it is possible to vary the parameters in rather wide range (ΔR=±0.1m, Δm_{acc}=±0.01kg) near the maximum without significant *Score* decrease.

Figure 6 shows the sensitivity of *Score* to L variation for the other parameters being constant (m_0=0.03kg). One can see that the difference of ΔL=±2.5sm is permissible. Also, figures 5 and 6 show that the small increase in the values of the aircraft characteristics from the optimum is better than small decrease.

At the end of the chapter it is worth to say a few words about the effects related with aircraft's moment of inertia. To fly along the circle the wing must be at some angle of roll. Changing the trajectory from one circle to another assumes the change of roll angle. It is required some time which depends on the moment of inertia and aerodynamical torques. So, as a recommendation, the airplane must have control surfaces (or other devices producing torque) sufficient for such quick maneuver.

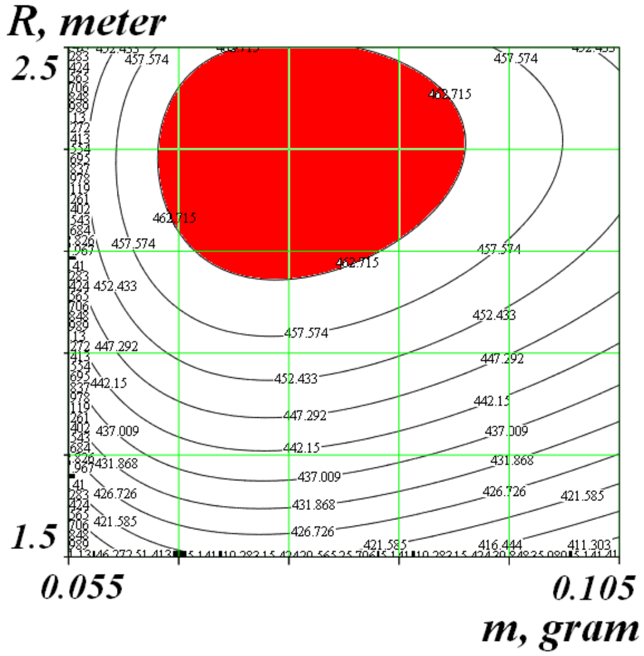

Figure 5: Score for various $m(m_{acc})$ and R.

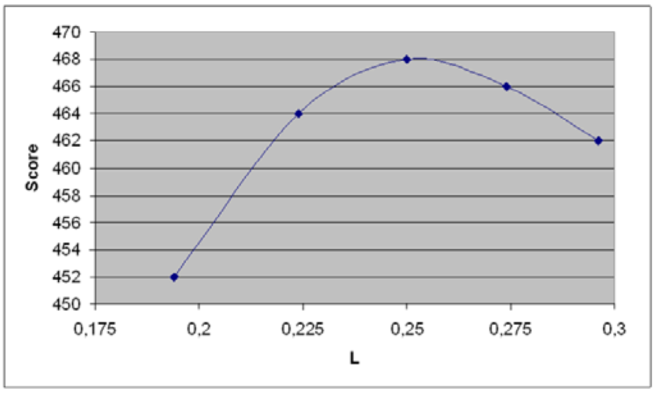

Figure 6: Score for various L.

In the case of insufficient torque for the maneuver required the problem of optimal control is much more complex and requires more thorough analysis. But this problem is out the scope of present investigation.

5 CONCLUSION

1. Optimal trajectory of MAV for EMAV indoor competition consists of two straight lines and two parts of circles.
2. Radii of circles is practically independent of aircraft parameters and is close to its optimal value. So, for the first approximation the trajectory can be assumed consisting of two circles.
3. The optimal velocity changes rather slow by m_0 change.
4. The ratio of accumulator mass to the total mass of aircraft for optimal design is practically constant for various m_0.
5. Maximal score decreases practically linearly with m_0 increase. Optimal mass and optimal wing span increase practically linearly with m_0 increase.

ACKNOWLEDGMENT

This work was carried out under support of Russia's President Grant for Young Scientists Support MK-2672.2008.8.

.

REFERENCES

[1] www.emav09.org
[2] Proceedings of EMAV-08. – Braunschweig, Germany, 8-10 July 2008
[3] T.J.Mueller, J.C.Kellogg, P.G.Ifju and S.VShkarayev. Introduction to the Design of Fixed-Wing Micro Air Vehicles. AIAA Education Series, 2007
[4] http://www.wes-technik.de/
[5] S.Serokhvostov, A.Kornushenko. "Experimental Investigations Of MAV Electrical Powerplant" Proceedings of EMAV-08. – Braunschweig, Germany, 8-10 July 2008