

CONCEPT OF MODULAR, SELF-SUPPORTING CABLE FOR POWERING THE HOVERING UNMANNED AERIAL VEHICLE

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ABSTRACT

Hovering unmanned aerial vehicles or drones can function as distant platforms for mounted sensors, as signal transceivers, or for other purposes. However, they must be tethered. The tether functions as a power cable that connects a tethered drone with a ground power unit. In this article, we developed a concept in which a power cable is of modular structure, consisting of mutually identical modules. Each module has motorised propellers and is capable of preserving itself in a given, hovering position. We formulated an equation for electric current that, for a given set of parameters, makes hovering of a drone with such a modular cable possible. The developed concept does not show significant improvement in maximum height reached by the drone. The underlying causes are extracted from a set of assumptions that define the concept.

KEY WORDS

unmanned aerial vehicles, tethered flying vehicle, modular cable, hovering

CLASSIFICATION

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INTRODUCTION

Unmanned Aerial Vehicles (UAVs) or drones are nowadays utilised in a variety of commercial and defence-related processes. They have contributed substantially to broadening of diverse human activities through conducting them using, at least partially, the third dimension. One may argue that rapid enlargement of set of activities in which UAVs are used, whether as a crucial or as an auxiliary device, point to the fact that their potential in conducting different activities is still far from being developed.

UAVs mutually differ regarding their function [1], henceforth regarding their different parameters such as are mass, flight endurance, maximal take-off weight, etc. along with different sets of sensors carried by UAVs.

One among the lines of development is a hybrid approach to the UAVs as mobile masts for *ad hoc* constructions in which they serve as sensor platforms or information transceiver hubs. In particular, a UAV is a heavier than air, carrying sensors and hovering on a fixed position during certain time interval. UAV's electric motors are powered by electric current from a ground source. Thus the UAV is tethered, using suitable cable presumably for transfer of energy from ground source to the UAVs. Tethered lighter than air UAVs have been, since quite a long time ago, regularly utilised for long-term surveillances. Yet, they are rather sensitive to atmospheric conditions such as wind or wind gusts, what interferes destructively with the possibility of their use.

In this article we restrict analysis onto UAVs which are tethered, heavier than air, ground-powered, hovering sensor-carrying platforms. An eventual purpose of development of such a concept is the possibility to use such constructions in cases of emergency, when one needs rapid deployment of transceiver with sufficiently large range and quality of transmission, often in adverse weather conditions. Such approaches have already undergone some development [2-6].

A rather important parameter of such an approach is maximal height on which the UAV can hover for some rather long period of time. Since cable connecting the UAV with the ground power source has its own weight, in this article we analyse the concept of modular, self-supporting cable that powers a UAV on its top [7].

Section two contains the model. Section three contains the results, and section four the discussion of the results. Section five concludes the article and lists possible further development.

CONCEPTUAL MODEL

ELEMENTS AND ENVIRONMENT

We develop the concept of a powering cable, connecting energy source on the ground with a UAV hovering above it. The structure of the cable is modular. Each cable consists of a, in principle initially indeterminate, number of mutually identical modules. Along with the modules, cable is formed with two adapters, one connecting it to a ground power unit (GPU) and the other to a UAV.

Crucial requirement imposed on the module is that is self-supporting, in other words that it can hover in a still atmosphere. Additional requirements imposed onto it are: (i) every possible actuator that a module may carry utilises current of a same quality that is transported by the cable from the GPU to the UAV, and (ii) it makes possible transportation of sufficient electric energy. The last requirement is in fact naturally forwarded basic function of an

energetic cable, the module representing its sub-structure. In addition, for the presently adopted conceptual level, we impose the requirement that (iii) module is constructed out of certified, commercially available components.

Because of the last requirement, the dimensions of the wire, an electric conductor, and of the insulating shielding are standardised. Similarly, the materials of all these parts are of prescribed composition. As a consequence, the linear density of the complete cable, λ , is given in a form of discrete values. For the purpose of making the calculations more tractable, we broaden the list of parameters of available cables onto continuously variable parameters. Naturally, at the end we restrict the possible outcome of calculations onto the set of existing cables' parameters.

Before proceeding, a note about the environment is appropriate. Eventually, such a modular cable is to be utilised in a variety of weather conditions, the more demanding the conditions the more important the rapid deployment of functional modular cable. In that sense one expect that there is a power reserve in the system that may be used to overcome effects of e.g. wind gusts. Along with that, one expects sufficient robustness of such a structure, making it rather suitable for manipulation. These requirements are partially fulfilled. First, robustness implies that every part of a cable is mechanically resistant to small shocks and moderate friction. That eventually reduces possible cables, since not all of them are predicted, and certified, for use in open space, subject to degrading and intense weather conditions. For the moment, we do not consider explicitly required power reserve, to be used for preserving the vertical, or close to vertical configuration in case of diverse weather conditions (wind gusts being a serious threat to such a geometry). Instead, we restrict our analysis at the conceptual level onto functioning of the cable in a still atmosphere, thus without significant wind and rainfall. It is reasonable to assume that, if a concept is logically consistent within some set of parameters, that there will be possible subset of these parametric values that would include also the aforementioned requirement for power reserve.

For further development of the concept, we assume that a module contains: four sets of mutually identical electric motor powered propellers; a frame; a processing unit; and two connectors aimed for establishing quick-release connection with other modules, or adapters found at both ends of the cable.

ELECTRIC CONDUCTORS

We extracted data from online sources of some of the commercially available electrical conductors aimed for use in open space. The data collected by no means form an exhaustive set, yet we did our best to form it as a representative set. However, if there had been a significant difference caused, its inclusion will change quantitatively some parameters but will not change the overall conclusions. From the collected data we formulated a constitutive relation between a linear density λ and a maximal direct current I that a conductor can carry for a long period of time:

$$\lambda(I) = k_{\lambda 1} \cdot I^2 + k_{\lambda 2} \cdot I + C_{\lambda}. \quad (1)$$

Values of coefficients were obtained after application of a least square method.

ELECTRIC MOTORS WITHIN A MODULE

For electric motors we choose Brushless Direct Current (BLDC) motors, following the representative type of existing small rotorcraft drones. From available data we formulated another constitutive relation, connecting mass of the motor m with the maximal power it can provide for a long period of time P_{el} :

$$m(P_{el}) = k_m \cdot P_{el} + C_m. \quad (2)$$

Following the approach described in the subsection *Electric conductors*, we obtained the coefficients in (2) for a representative, yet definitely not complete set of electric motors. In particular we obtained $k_m = 2 \cdot 10^{-4} \text{ kg} \cdot \text{W}^{-1}$ and $C_m = 2,26 \cdot 10^{-2} \text{ kg}$, values that are used throughout this article.

SELF-SUPPORTED MODULE

We assume that a module is capable of self-supporting it. Of course, that must be considered carefully, since a module has to be connected to other modules forming a closed electrical circuit. In that way we consider a stationary case, in which the lift generated by the propellers connected to BLDC motors is in balance with the weight of the module. A general approach is that the total lift must be somewhat larger than the total module weight, hence we start with the following equation for stationary case:

$$\varepsilon T_{\Sigma} = G_{\Sigma}, \quad (3)$$

with factor ε taking into account stated difference between the maximal total lift T_{Σ} and total weight G_{Σ} , lift being equal to thrust of the propellers from all the motors, which is in the case of quadrotor configuration of the propellers equal to

$$T_{\Sigma} = 4T, \quad (4)$$

with T being the lift provided by a single propeller. In (3) and (4) we did not explicitly take into account aerodynamic drag of the module. Implicitly, it is incorporated in factor $\varepsilon < 1$.

Total weight equals

$$G_{\Sigma} = \lambda(I)Lg + [4m(P_{el}) + m_0], \quad (5)$$

with L being the length of the module, and m_0 mass of all other components – a frame for motors, control unit and connectors – which are considered applicable with negligible modifications for different L and I .

Electrical power P_{el} is in motors transformed into mechanical power P_{mech} . It is connected with the thrust by the following relation for hovering rotor:

$$P_{mech} = \frac{T^{3/2}}{\sqrt{2\rho A}}, \quad (6)$$

where A represents area of the circle described by the rotating propeller. Electrical and mechanical power are related with the efficiency factor $\eta < 1$:

$$P_{mech} = \eta \cdot P_{el}. \quad (7)$$

Finally, in case of direct current one has relation

$$P_{el} = U \cdot I, \quad (8)$$

where voltage U is considered equal for each of the modules. Current I propagates through all the modules. There are different ways to electrically power all the control units and the motors. Here we consider the case in which electrically all the control units are connected mutually parallel. That is not the only case but, from the point of view of redundancy and thereby introduced safety level, represents suitable starting point for analysis. The opposite case would be that of the minimal redundancy, in which all control units are serially connected. In case of parallel connections the current flowing through modules differs and is the largest in the module connected to GPU. Let us consider that we have n ($n = 1, 2, \dots$) modules. In that case current through the module connected to GPU equals nI and the total power becomes

$$P_{el} = U \cdot I. \quad (9)$$

Expressions (1)-(8), when combined, bring about the following equation for the current through the module

$$C_1 \cdot I^2 + C_2 \cdot I - C_3 \cdot I^{2/3} + C_4 = 0. \quad (10)$$

with the straightforward introduced coefficients

$$C_1 = k_{\lambda 1} L g n^2, \quad (11)$$

$$C_2 = k_{\lambda 2} L g n + 4k_m g U, \quad (12)$$

$$C_3 = 4 \varepsilon (2 \rho A \eta^2 U^2)^{1/3}, \quad (13)$$

$$C_4 = C_\lambda L g + (4 C_m + m_0) g, \quad (14)$$

System (10)-(14) was solved numerically for a range of lengths L with constant voltage $U = 12$ V and other data for set 1 of conductors (Table 1). We consider only values of current that are real, not complex numbers.

RESULTS

Coefficients in the constitutive relation (1) for three sets of conductors are given in Table 1. Sets differ by the material of the conducting wire and insulating shield. Corresponding graph of the relation (1), for one of the sets of conductors, is shown in Figure 1. Precise values differ for other sets of conductors, but the quadratic form approximates the data well.

Table 1. Coefficients of constitutive relations $\lambda(I)$.

Set of conductors	$k_{\lambda 1}, \text{kg} \cdot \text{m}^{-1} \text{A}^{-2}$	$k_{\lambda 2}, \text{kg} \cdot \text{m}^{-1} \text{A}^{-1}$	$C_\lambda, \text{kg} \cdot \text{m}^{-1}$
1	0,00010	0,0030	0,0082
2	0,00002	0,0046	0,0634
3	0,00003	0,0058	0,0832

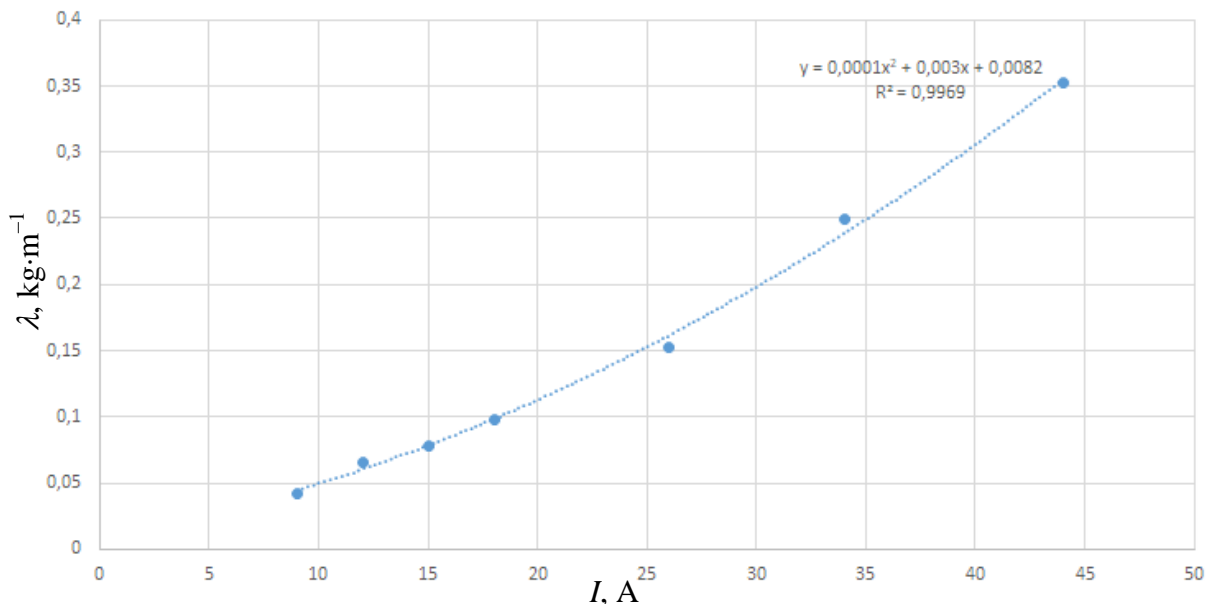


Figure 1. Linear density of the wire in dependence of the maximal constant current through it, as expressed by the constitutive relation (1) for conductors of set 1.

Constitutive relation (2) is shown in Figure 2 for a representative set of motors. Precise values would differ for more exhaustive set of electric motors, but one may argue that linear relation would approximate data with a sufficient degree in the conceptual approach.

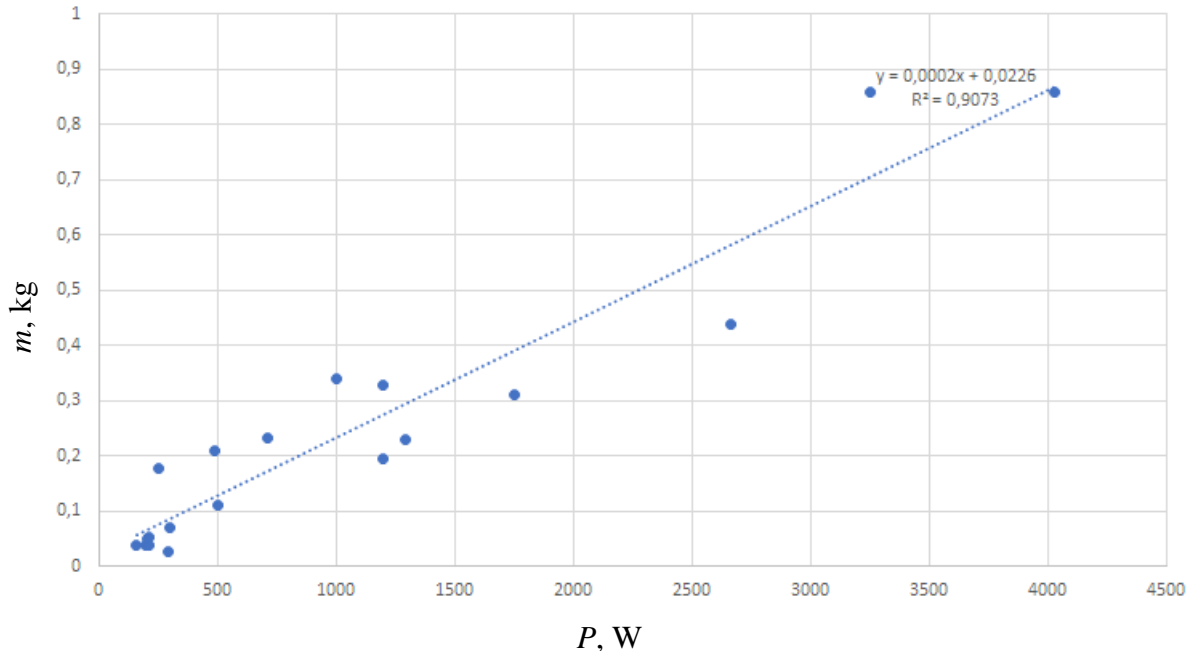


Figure 2. Mass of an electric motor in relation to its maximal generated power, as expressed by the constitutive relation (2) for chosen set of BLDC motors.

Current I through the conductors, obtained by numerically solving equation (10). The only physical solution is shown in Figures 3 and 4. In calculations value $\varepsilon = 0,5$ was used. Accompanied total power which should be provided by GPU is shown in Figure 5.

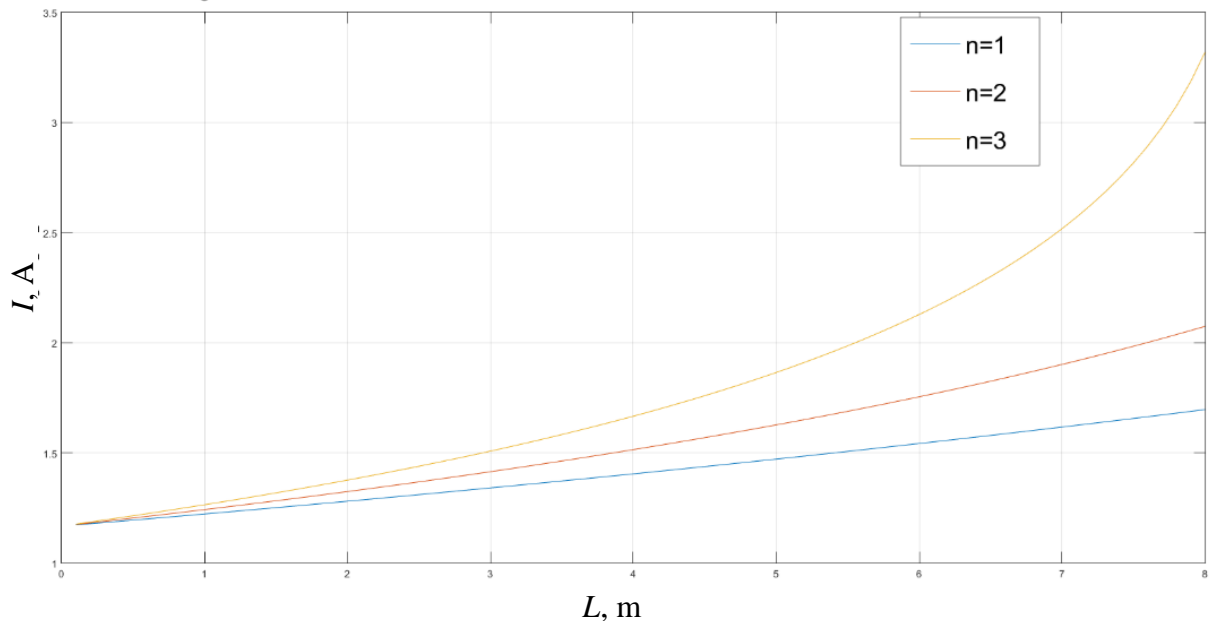


Figure 3. Current I , a solution of (10), in relation to the module length L , for set 1 of conductors as described in Table 1. Voltage of GPU is 12 V and number of segments equals $n = 1, 2, \text{ or } 3$.

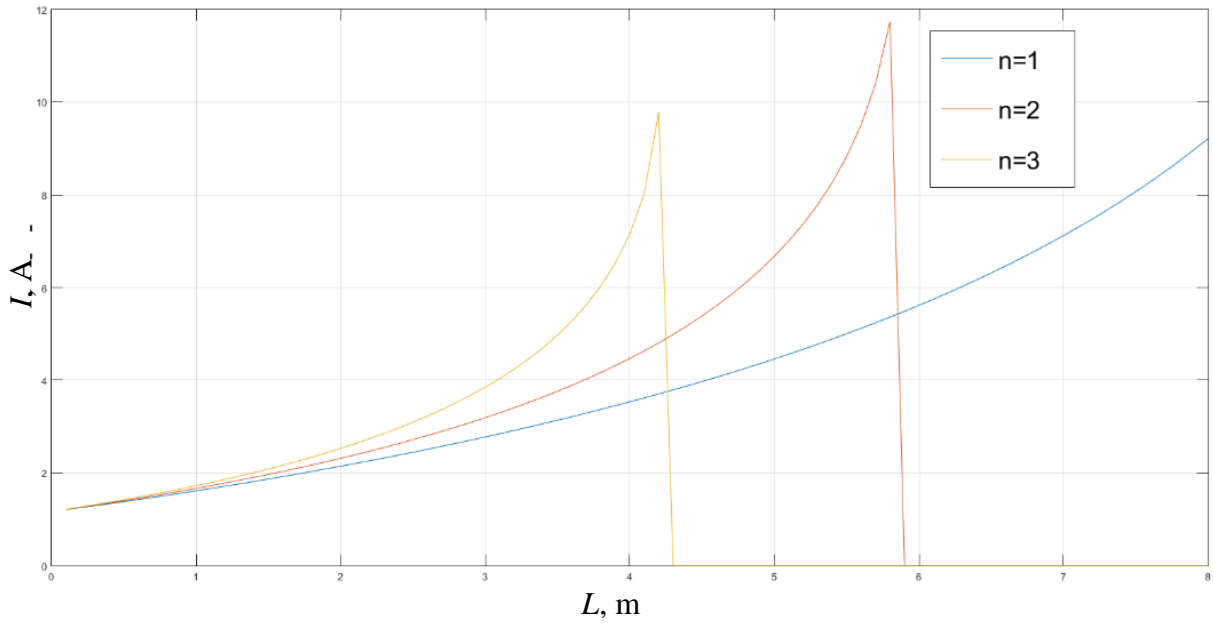


Figure 4. Current I , a solution of (10), in relation to the module length L , for set 3 of conductors as described in Table 1. Voltage of GPU is 12 V and number of segments equals $n = 1, 2$, or 3.

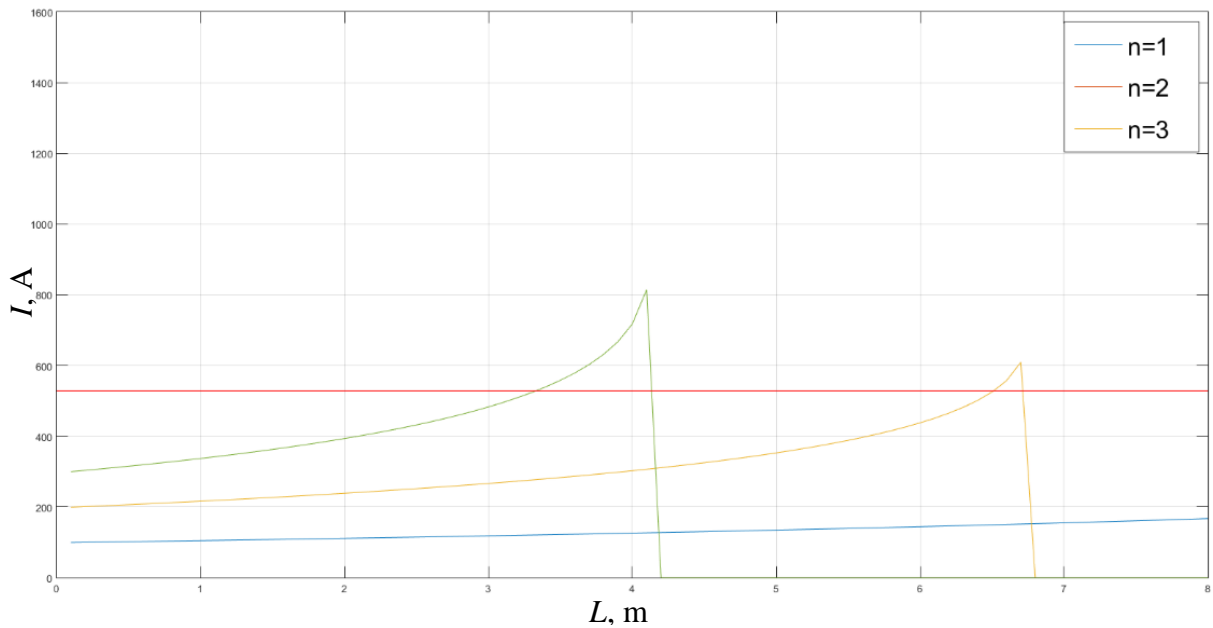


Figure 5. Total power (9), in relation to the module length L , for set 1 of conductors as described in Table 1. Voltage of GPU is 12 V and number of segments equals $n = 1, 2$, or 3.

Total length of the cable is given in Table 2 for analysed combinations. All combinations belong to the same configuration in which modules are mutually identical and can carry total current flowing through a module.

Table 2. Total length of the cable for all sets of conductors and different number of modules.

Set of conductors	Number of modules		
	1	2	3
1	14 m	13 m	12 m
2	8 m	9 m	9 m
3	6 m	7 m	6 m

DISCUSSION

Modular structure of the powering cable for making possible longer durations of hovering of drones is analysed. In prescribed configuration, on the conceptual level, modules are identical and carry uniquely defined current. Dependence of the total mass of the module on the allowed maximal current is well described with a quadratic polynomial. For a given class of electric motor, dependence of their mass onto generated power is sufficiently well described by a linear function. Naturally, owing to the numerical character of the solutions, more complex dependences were possible. Yet, having in mind that this is a conceptual level of approach and that underlying data do not form an exhaustive set of available data, the stated form of functions, as one may argue, is the optimal one.

A problem is transformed into an algebraic function that finally brings about the physically unique current flowing through the lowest module. That gives an insight into the general, nonlinear dependence of that current on a length of a module.

This is aligned with the fact that the longer a segment the larger its mass, bringing about a requirement of using a stronger electric motors, that additionally enlarge the module mass. For a fixed voltage large power implies larger current which, in a form of a feedback loop, requires larger cross-section of a module, eventually its larger mass. Self-consistently a unique relation between a current and a length of modules is obtained. It parametrically depend on a total number of segment having in mind the particular way of electrically connecting the modules. For any number of segments, there is a definite maximal length of a module because for larger lengths there is no physical current making possible self-sustained hovering of a module.

CONCLUSIONS AND PERSPECTIVES

Possibility of using hovering drones in *ad hoc* networks for transmitting and receiving data is possible, yet rather vaguely approached, application of drones. For their longer contributing in such an application a possible approach is to have wired connection of a drone with ground power unit. Among the variety of conceptually different realisation belonging to such an approach in this article we analysed modular approach to powering cable with particular emphasis on the self-sustained hovering of a module. Preliminary practical considerations brought about the initial set of requirements imposed onto the analysed structure, which eventually was transformed into a mathematical model, numerically solved.

Results point to the fact that the concept developed does not bring any significant value to formal solution of the problem. In fact, there is no significant difference in total height of the cable depending on different number of its modules; a single cable represented with total number of modules equal to 1. That is traced down to simultaneous rise in cross-section of a conductor making possible larger flows needed for stronger electric motors, which are eventually required for making possible self-sustained hovering of the very module.

That is a consequence related to restriction imposed onto the concept in particular the rather significant redundancy, electrically parallel connections of control units with motors among modules.

A significant improvement of the modular in comparison with non-modular cable would imply different scaling of current with length or with number of modules. Here, we are not interested in quantitative improvements by taking into account different cables or electric motors, specially constructed to have more pronounced specific quantities. On the contrary, we are interested in qualitatively different scaling of current with the module length. For that purpose we consider that optimal solution to the problem of constructing a modular powering

cable for a hovering drone could be achieved with significantly different approach to redundancy in which electrical connections are implemented differently that in the analysed article [7]. One, naturally, expects that preserving the level of safety, then, would imply additional measures that are not explicitly represented in the formalism, but that forms a unique combination with the analysed construction.

DISCUSSION

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