Podgaets A.R., Ockels W.J. Flight control of the high altitude wind power system. *Proceedings of the 7th Conference on Sustainable Applications for Tropical Island States* (Cape Canaveral, Florida, USA, June 3-6 2007)

Flight Control of the High Altitude Wind Power System

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***Abstract*-Closed loop Laddermill flight control problem is considered in this paper. Laddermill is a high altitude kites system for energy production. The kites have been simulated as rigid bodies and the cable as a thin elastic line. Euler angles and cable speed are controls. Flight control is written as a fusion of two approaches: design of experiments and stochastic optimization. Such combination ensures finding global optimum for any reasonable number of parameters and objectives in a reasonable time while also collecting some information about sensitivities – these two features are much harder to achieve by other means. Robustness has been formulated as an additional objective. We found the system very steady despite big variations of wind velocity. The resulting optimal trajectories can be also used as a first iteration for open loop control algorithms.**

INTRODUCTION

Tropical islands have big number of windy days which may mean that strong wind energy sector can become a good asset for them. A lot of research has been done worldwide on using high altitude winds for clean energy production (e.g., [17, 43, 44]). The concept for sustainable energy production called Laddermill [35] (see fig. 1) is known for 11 years now [36] and refers to the system of kites on one rope that drives the generator as kites pull it. The benefits of this approach to energy production is a low weight, low cost and simplicity of the structure, installation and maintenance [37, 27]. Theoretical investigation promises capabilities of a vast power output [28]. The concept has been successfully tested on a small scale with a single kite and several authors contributed to simulation of the kite systems (e.g., [31, 52]) but a robust controller has not been yet published for this application.

A few methods for addressing stability of kites and parachutes are presented in [54, 45, 33]. However, being primarily design choice tools, they are not suited for robust control. Possible kite control actuators are shown in [7, 8, 29]. Among recent optimization studies about kites is a design optimization paper [24], model-predictive control studies [22], [6] and [53] are in different stages of preparation for publishing. Receding horizon and Lyapunov's parameters methods are used in all of them while control functions and optimization features are different: [6] and [53] formulate fast control for equations of motion while [22] employs Lagrange equations and full scale control, evolutionary optimization is used in [53] while [6] and [22] use multiple shooting. Control functions in [6, 53] are yaw, lift aerodynamic coefficient and cable length, and in [22] – roll, attack angle and cable length.

Laddermill

Laddermill is designed to become an alternative to windmills. It looks like a *ladder* of kites and generates electricity from wind as a wind*mill*. When kites pull the rope the winch rotates and dynamo generates energy. Laddermill is a collective name for several designs; a rotating ring [38, 32] is historically the first. A 'yo-yo'-like system is described in [47] and pumping Laddermill is pictured below.

Fig. 1. Artistic drawing of a Laddermill

All designs of Laddermill have several benefits in comparison with conventional windmills. At first, they do not have dramatic cost curve due to the absence of blades and a pole; cost increase for larger than 5 MW designs is much more close to linear, in theory making such machines feasible. The required thickness of cable is a limiting factor and probably

100 MW or a bit more would be a technological limit of designs based on conventional Dyneema cables [28]. Next to it is a relatively low cost of installation and even mobility – there is no pole to dig into the ground and no blades to transport. Finally, Laddermill has a choice of altitudes: if there is not much wind on 400 m, let's go to 300 or 500!

Laddermill's ground station includes all basic parts of a windmill chamber: climatic camera, motor-generator, battery, brakes, etc. The main cable we are using now is made of Dyneema SK-60 fibers, and potentially it can be made of even stronger fibers or even nanoropes of space lift projects. The kites we use now are conventional surfkites because of their long design and exploitation record. However specially designed gliders [5], inflatable [4], twinskin [9] or lightweight [3] kites, parawings [55] and parachutes [12] can produce even better results.

Pumping Laddermill operates as follows. At first the first kite is launched into the air. Ground station unreels the rope while the first kite pulls the rest of the kites until they are all in the air. When the kites are considered launched, the ground station switches into dynamo mode and starts generating electricity and charging the battery. The length of the cable when this happens is called starting length. During generating energy the kites are flying in figures "eight". Their roll angle is following a harmonic function and yaw angle changes according to the direction of current apparent wind. Kites' pitch is zero. When the total length of the rope is achieved the kites are depowered, their roll is set to zero, ground station switches into motor mode and the rope is reeled back in to the starting length. By depowering we mean that angle of attack is set to zero lift value (approximately -6 degrees for the chosen kite) by controlling pitch. After that the cycle repeats.

Thus, some of the basic design parameters of a pumping Laddermill include aerodynamic coefficients, areas and masses of kites, their number and distances between them along the cable, starting and total cable length, stiffness and breaking strength. The control parameters that determine Euler angles in each moment of time are reel out and reel in speed, period and magnitude of one figure "8".

METHODS

Mathematical model of Laddermill

The Laddermill is a flexible multi-body structure consisting of the kites and the cable. Because of negligible deformations of the arc the kites has been simulated as rigid bodies with surf kite's airfoil in cross-section. Although techniques like flying in circles [50] allow obtaining aerodynamic coefficients, we found them for a surfkite from simulation of the airflow around surfkite's airfoil. The cable is considered elastic, thin and light. Three dimensional equations of motion are used to describe the movement of the kites [39]:

$$\dot{\boldsymbol{v}}_j = \left(\boldsymbol{D}_j + \boldsymbol{L}_j - \boldsymbol{T}_j + \boldsymbol{T}_{j+1}\right)/m + \boldsymbol{g}, \tag{1}$$

$$\dot{\boldsymbol{r}}_j = \boldsymbol{v}_j + \boldsymbol{wind}, \tag{2}$$

$$\boldsymbol{D}_j = -\tfrac{1}{2}\rho S c_D v \boldsymbol{v}, \tag{3}$$

$$\boldsymbol{L}_j = \tfrac{1}{2}\rho S c_L v \boldsymbol{d} \times \boldsymbol{v}, \tag{4}$$

$$\boldsymbol{T}_j = \Delta l_j E A \boldsymbol{l}_j / \left(l_{j0} r_j\right), \tag{5}$$

here j is the number of the kite (from 1 to N),

$\boldsymbol{r} = (r_1, r_2, r_3)$ and $\boldsymbol{v} = (v_1, v_2, v_3)$ are the position and velocity of the kite relative to the airflow,

$\boldsymbol{wind}$ is wind velocity,

m, S, c_D and c_L are kite's mass, projected area and aerodynamic coefficients,

$\boldsymbol{d} = (d_1, d_2, d_3)$ is a unit vector pointing from the left wing of the kite to the right one;

$\boldsymbol{D}$, $\boldsymbol{L}$ and $\boldsymbol{T}$ are the forces of drag, lift and tension respectively.

Flight control problem

The equations of motion (1) – (5) can be rewritten as

$$\dot{x}(t, \boldsymbol{u}, \boldsymbol{x}) = f(t, \boldsymbol{u}, \boldsymbol{x}), \tag{6}$$

here $\boldsymbol{x}$ is the vector of coordinates and velocities of all kite with $n = 6N$ components

$$\boldsymbol{x} = \left(r_{11}, r_{12}, \ldots, r_{16}, v_{11}, v_{12}, \ldots, v_{16}, \ldots, v_{N6}\right),$$
$$\boldsymbol{x}(t) \in D \subset \Re^n \tag{7}$$

and $\boldsymbol{u}$ is the vector of controls

$$\boldsymbol{u}(t) = \left(v_l(t), \phi(t), \theta(t), \psi(t)\right), \tag{8}$$

$$\boldsymbol{u}(t) \in U \subset \Re^3. \tag{9}$$

Roll φ, pitch θ and yaw ψ affect components of vector $\boldsymbol{d}$ (4) in Earth-fixed reference frame [11] and v_l is a cable speed. The set of possible coordinates and velocities D dictates that all kites should be above the ground at all times and the set of possible controls U defines possible attitude angles with which kites can fly (from $-\pi/2$ to $\pi/2$). . Cable speed is limited by 1 m/s from below and 10 m/s from above. There are also constraints on how fast control can be executed:

$$\boldsymbol{\omega}_0 < \dot{\boldsymbol{u}}(t) < \boldsymbol{\omega}_1 \tag{10}$$

with the practical limit for each angular ω evaluated as $6\pi/S$. Thus, a 6 m^2 kite can execute a complete turn in 2 seconds and 20 m^2 requires almost 7 seconds to turn.

Simulations during which the kites crash or spend more energy than produce are immediately interrupted. Unless this happens horizon of this optimal control problem is t_1=300 s:

$$t_0 \le t \le t_1(\boldsymbol{u}(t)). \tag{11}$$

It is a time sufficient for several cycles of energy production even for the slowest cycle.

The main objective of this research is energy production

$$\boldsymbol{\Phi} = \left(\Phi_1, \Phi_2, \Phi_3\right) \in \Omega \subset \Re^3 ,$$

$$\Phi_1 = \int_{t_0}^{t_1} \boldsymbol{T}_0(t) \cdot \boldsymbol{V}_0(t) dt \to \max_{\boldsymbol{u}(t)} , \tag{12}$$

however there are other considerations the relevance of which needs investigation. One of them is the radius of the area which Laddermill occupies:

$$\Phi_2 = \max_{t \in [t_0, t_1]} \sqrt{r_{j1}^2 + r_{j2}^2} \to \min_{\boldsymbol{u}(t)} . \tag{13}$$

Finally, the last objective assesses the robustness of flight trajectory and will be constructed below. The problem with objectives (12), (13), (15) controlling functions (8) and constraints (7), (9), (10) and (16) is the optimal control problem with three objectives, fixed start, open end (11) and constraints. The resulting problem is a robust optimal control problem with fixed start, open end, three objectives, four controls and constraints.

Introduction of uncertain wind

The possibility of achieving high energy production levels depends not only on overall performance of Laddermill and it's optimal control but also on following the optimal trajectory. That is why addressing stability is an essential part of Laddermill's mathematical description. One of the factors that affects Laddermill's performance is the wind. For example there could be a wind gust that will dramatically decrease Laddermill performance in a given moment. Thus the robust control methods should be used. The fastest way to do so is calculating Lyapunov parameters [30] however we argue the possibility to fully understand the role of uncertain wind by investigating only one trajectory and not looking in the resulting change of energy production. More thorough possibilities include fuzzy logic [25] and interval computation, adaptive control [13, 14] and Bayesian networks [21], approximate dynamic programming [57] and reinforcement learning [2], evolutionary algorithms [10, 16], swarm intelligence, random forests, neural networks [46], support vector machines, multivariate adaptive regression splines [26], dominance-based filters [56], and others [23]. Yet another approach we use here originates directly from Lyapunov's definition of stability [19, 20] and does not employ any additional mathematics.

Lyapunov's definition is first transformed into the definition of stochastic stability

$$\delta_w \left| P\left(\left| w - w^* \right| < \delta \right) \geq P^{**} \Rightarrow P\left(\left| E - E^* \right| < \varepsilon \right) \geq P^* \right. , \tag{14}$$

which is then turned into a pair of constraints [18]:

$$\Phi_3 = \varepsilon \to \min_{\boldsymbol{u}(t)} , \tag{15}$$

$$\begin{cases} P\left(\left| w - w^* \right| < \delta \right) \geq P^{**} \\ P\left(\left| E - E^* \right| < \varepsilon \right) \geq P^* . \end{cases} \tag{16}$$

Equation (15) reads: let us find such trajectory that minimizes trust interval of energy deviation ε for a given interval of wind deviation δ with given trust levels $P^*=P^{**}=0.99$.

Multi-objective approach

There are several approaches for numerical solution of multi-objective optimal control problems – the principle of maximum [41], controls decomposition [15] and all the types of methods listed in the previous section. However, [34] have shown that continuous optimization problems cannot avoid a curse of dimensionality. Although it can be smoothed by introducing random jumps into the algorithm [1], only design of experiment type of approaches that map the feasible parameter space can completely solve this problem. Exact version of this approach used in this research is called parameter state investigation [42]. It has been primarily developed for design choice [49] but can be also efficiently employed in flight control [40].

Parameter state investigation method is finding feasible points by mapping the region of possible solutions in a certain fashion and then indexing results for visualization. LP_τ sequence [48] has been used in this research because it guarantees that for every given step in every hypercube there will be one and only one test point [51].

After finding feasible solutions and consequent refining the parameters of original optimization problem the method obtains Pareto set, the collection of all nondominated points in objective space. A nondominated point corresponds to an efficient solution in decision space. An efficient solution is a feasible solution for which an improvement in one objective will always lead to a deterioration in at least one of the other objectives. The nondominated set conveys trade-off information to a decision maker who makes the final decision.

RESULTS

The following values of parameters have been used:

Laddermill:

Number of kites – 5,
Kites type – inflatable surfkite,
Aspect ratio – 3,
Zero lift angle – –6 degrees,
Mass of each kite – 5 kg,
Area of each kite – 20 m^2,
Distance between kites – 5 m,
Starting cable length – 75 m,

Total cable length – 125 m,
Cable stiffness – 112 kN,
Cable breaking strength – 40 kN.

Wind conditions:
Wind speed – 15 m/s (Bft 7, 30 kt),
Wind gust duration – 0,5 – 5 s (even distribution)
Wind gust speed – 0 – 15 m/s (normal)
Wind gust direction – 360 degrees (even)
Only one wind gust is happening at a time.

Optimization:
Horizon – 300 s,
Time step – 0,001 s,
Average number of trajectories in a sample – 9,
Number of test points – 1024,
Number of feasible solutions – 864,
Number of solutions in Pareto set – 12.

Optimal solution:
Reel out speed – 6,96 m/s,
Reel in speed – –8,58 m/s,
Period of one figure “eight” – 3,58 s,
Magnitude of figure “eight” – 22,5 degrees.

The amount of electric energy produced for the optimal solution is roughly 0,5 kWh per minute of operation (fig. 2).

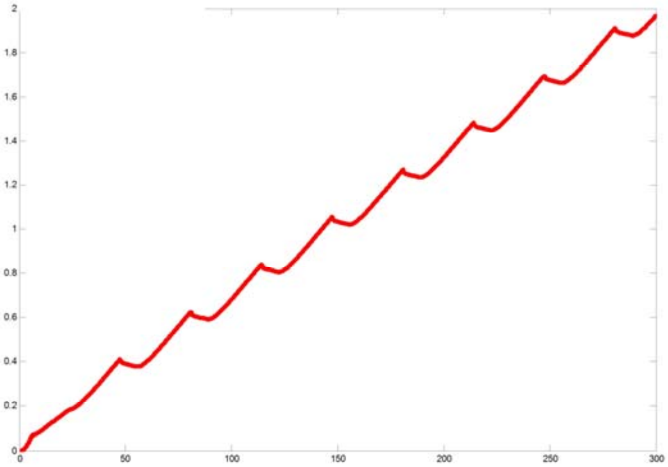

Fig. 2. Energy production over time, kW h

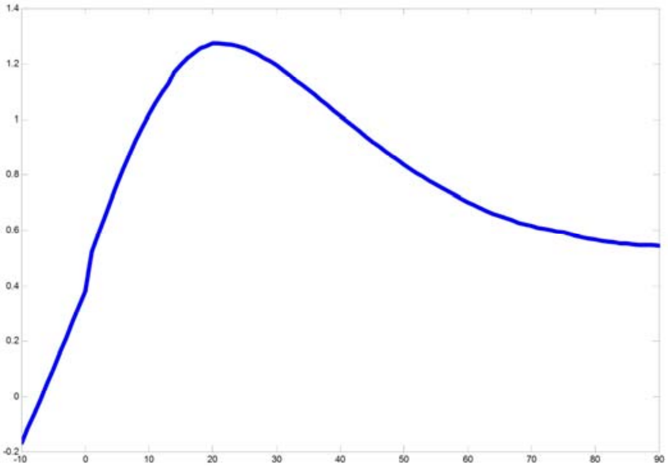

Fig. 3. Lift over attack angle for surfkite’s airfoil

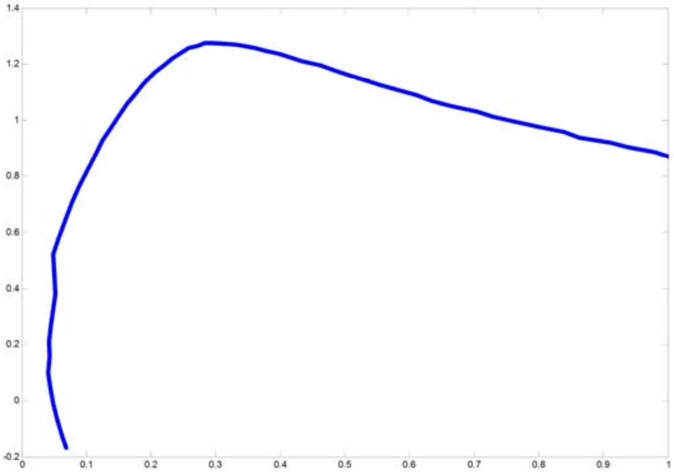

Fig.4. Lift-drag polar for surfkite’s airfoil

Figures 3 and 4 show aerodynamic coefficients of the kite found from CFD analysis of airflow around its airfoil.

Trajectory of the whole Laddermill system during the first minute of operation can be found on fig. 5. It covers launch and the first cycle of operation: reeling up and down. The graph ends in the beginning of reeling up for the second time. When the first kite is launched the rest get dragged into the air automatically after reaching their rope length. They make a characteristic rapid arc ascent that always happens when you put tension on kite’s lines, then move back as a pendulum in order to find their equilibrium and then start their controlled ascent. After reaching the starting cable length the kites start flying in figures “eight” (this and previous trajectory are drawn without wind gusts for better view) – see fig. 6. When the total length of the cable is reached the kites are depowered and start descent.

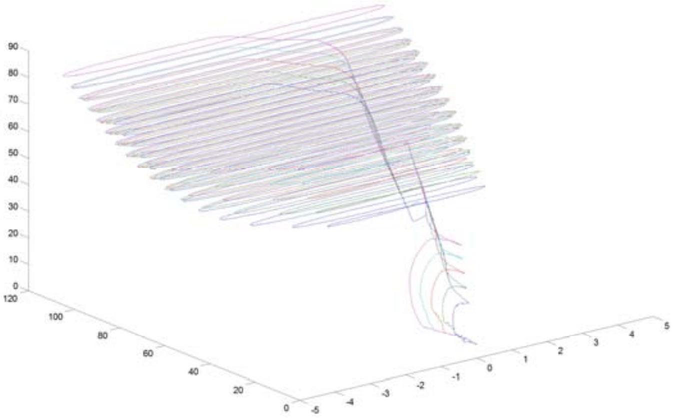

Fig. 5. One cycle of reeling out and in

Roll control that causes this movement is shown on fig. 7 which shows one cycle of “figure-eighting”. The graph starts right before the finish of the launch and ends in the beginning of descent.

Kite’s angle of attack is shown on fig. 8. As there are lines for five kites at once, the picture during the launch is a bit dirty. High angles in the first three seconds are produced

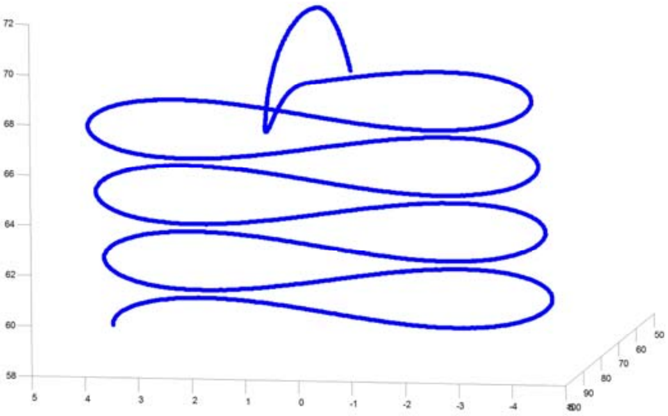

Fig. 6. Ten seconds of flight of the first kite

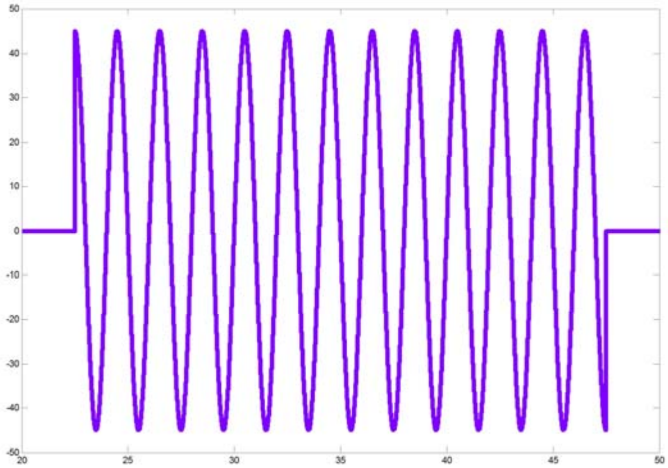

Fig. 7. Roll angle of the 1st kite over time

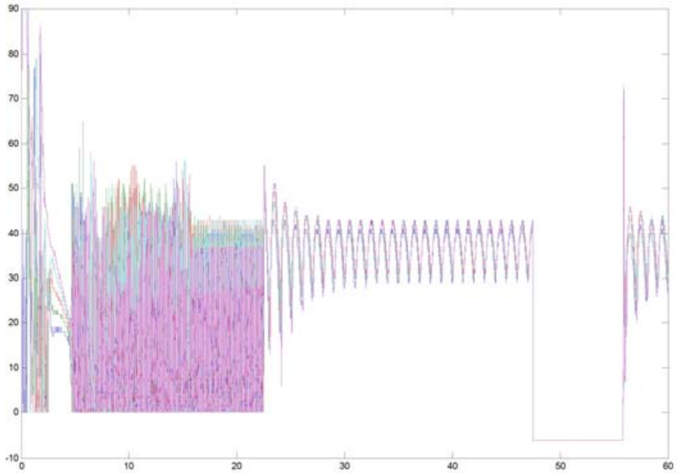

Fig. 8. Angle of attack of the kites

by the kites that are tumbling on the ground. Then there is a smooth moment when the tension is applied – here you see how short this large arc movement is. During the first ascent the kites are moving rather chaotic, then you see the influence of "figure-eighting" and – finally – descent when angle of attack is set to zero lift angle.

Corresponding cable tension is shown on fig. 9.

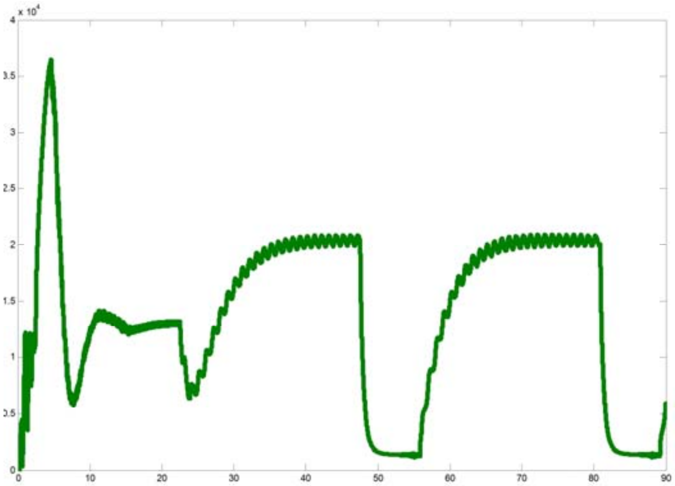

Fig. 9. Cable tension, N

The arc that the kites perform in 3-5 seconds of flight gives the highest tension which is almost twice as big as any other operations. The small waves of tension are caused by "figure-eighting": passing the middle of figure "eight" reduces tension while active turning on the ends increases it.

DISCUSSION

- Uncertain wind conditions proved to be not a threat for a fully controllable kite: all the crashes happened solely due to a poor control, energy production mostly benefited from random gusts of wind.
- Another observation is that bigger energy production means less stability in the electric power.
- The faster are the movements of the kite the bigger is the influence of wind gusts on the change in energy production.
- The best kite trajectory has a short period and as fast kites movement as possible.
- Small magnitudes of the figure "eight" produce more vertical ascent.
- Control of the kite is based on kite's search of equilibrium so it is a bit delayed. Turn in advance.
- Required thickness of the cable can be dramatically reduced by doing something clever in the first five seconds of the flight – may be variable cable speed can smooth them.
- The amount of power produced is practically the same as for a windmill with the same swept area. The diameter of blades of such windmill would be around 11 meters.

CONCLUSIONS

A concept called Laddermill has been simulated in this paper. Five surfkites in Bft 7 wind are generating 2 kilowatt-hours every four minutes which is the same as power output of windmill of the same swept area. However, Laddermill has also a choice of altitudes and much lower cost of construction which makes it a more flexible and mobile solution.

REFERENCES

1. Atkeson C.G. Randomly Sampling Actions In Dynamic Programming. *Proceedings of the 2007 IEEE Symposium on Approximate Dynamic Programming and Reinforcement Learning*, 2007

2. Atkeson C.G., Moore A.W., Schaal S. Locally weighted learning. *Artificial Intelligence Review*, 1997, Vol. 11, pp. 11-73.

3. Berezina A.V. Designing a kite for a wind electric station. Project report. Perm State Technical University, 2006

4. Breuer J.C.M. An inflatable kite using the concept of tensairity. MSc thesis. EMPA, TU Delft, 2006

5. Breukels J., Ockels W.J. Tethered wing design for the Laddermill project. *Windtech international*, 2006, No. 8, pp. 6-9

6. Canale M., Fagiano L., Ippolito M., Milanese M. Control of tethered airfoils for a new class of wind energy generators. *Conference on decision and control*, 2007 (accepted)

7. Carpenter, H.G., “Tethered Aircraft Having Remotely Controlled Angle of Attack,” US Patent 5,931,416.

8 Carpenter, H.G., “Tethered Aircraft System for Gathering Energy From Wind,” US Patent 6,254,034.

9. Chadov I.S. Stress-strain state analysis of a traction kite. Project report. Perm State Technical University, 2006

10. Coello Coello C.A., Van Veldhuizen D.A., Lamont G.B. *Evolutionary Algorithms for Solving Multi-Objective Problems*, Kluwer Academic Publishers, 2002

11. Cook M.V. Flight dynamics principles. John Wiley & Sons Inc., 1997

12. Dobrokhodov V.N., Yakimenko O.A., Junge C.J. Six-degrees-of-freedom model of a controlled circular parachute. *AIAA Journal of Aircraft*, 2003, vol. 40, No. 3, pp. 482-493.

13. El-Ayadi M.H. Nonstochastic adaptive decision fusion in distributed-detection systems. *IEEE Transactions on Aerospace and Electronic Systems*, 2002, vol. 38, No. 4, pp.1158-1171

14. Fan M.K.H., Tits A.L., Doyle J.C. Robustness in the presence of mixed parametric uncertainty and unmodeled dynamics. *IEEE Transactions on Automatic Control*, 1991, vol. AC-36, no. 1, pp. 25-38

15. Fletcher C.A.J. *Computational Galerkin methods*. Springer-Verlag , 1984

16. Fonseca C.M., Fleming P.J. Genetic algorithms for multi-objective optimisation: Formulation, discussion and generalization. *Proceedings of the 5th International Conference on Genetic Algorithms*, 1993, pp. 416-423

17. Fry C.M., Hise, H.W. *Wind driven, high altitude power apparatus*. US Patent 4084102, 1978.

18. Gitman M.B. Solution method for stochastic optimization of metal processing technological process with stochastic distribution of initial conditions. *Mathematical Modeling*, 1992, No. 1, pp. 20-25

19. Gitman M.B., Trusov P.V., Yakubovich M.B. Stability of contracted beam with stochastic distribution of initial parameters. *Proceedings of XIII School on Simulations in Continuous Medium Mechanics*, 1999, 152-159

20. Gitman M.B., Yakubovich M.B. On stability of deformation with stochastic distribution of initial parameters. *Transactions of Perm State Technical University: Mathematics and Applied Mathematics*, 1996, No. 1, pp. 61-66

21. Glumov V.M., Zemlyakov S.D., Rutkovskii V.Y., Suhanov V.M. Technical controllability of automated space module. *Automatics and Telemechanics*, 2001, No. 3, pp. 31-44

22. Houska B., Diehl M. Optimal control of towing kites. *Conference on decision and control*, 2007 (accepted)

23. Iyer N., Bonissone P.P. Automated risk classification and outlier detection. *CD Proceedings of the IEEE Symposium on Computational Intelligence in Multicriteria Decision Making*, 2007 1-4244-0702-8/07

24. Jackson P.S. Optimum loading of a tension kite. *AIAA Journal*, 2005, vol. 43, no. 11, pp. 2273-2278

25. Karr C.L. Design of a adaptive fuzzy logic controller using a genetic algorithm.*Proceedings of the Fourth International Conference on Genetic algorithms*, 1991

26. Keel L.H., Bhattacharyya S.P., Howze J.W. Robust control with structured perturbations. *IEEE Transactions on Automatic Control*, 1988, Vol. 33, pp. 68-78

27. Lansdorp B., Remes B., Ockels W.J. Design, construction and testing of the first 2 kW Laddermill. *Proceedings of IX World Renewable Energy Congress*, 2006

28. Lansdorp B., Ockels W.J. Design of a 100 MW Laddermill. *Proceedings of 7th World Congress on Recovery, Recycling and Re-integration*, 2005.

29. Lansdorp B., Ockels W.J., Remes B. Test results of a radio controlled surfkite for the Laddermill. *CD Proceedings of the World Wind Energy Conference, 2005*

30. Leitmann G., Pandey S. Aircraft control for flight in an uncertain environment: takeoff in windshear. *Journal of optimization theory and applications*, 1991, vol. 70, No. 1, pp. 25-55

31. Loyd M.L. Crosswind kite power. *Journal of Energy*, 1980, vol. 4, No. 3, 106-111

32. Meijaard J.P., Ockels W.J., Schwab A.L. Modelling of the dynamic behaviour of a Laddermill, a novel concept to exploit wind energy. *Proceedings of the III Symposium on Cable Dynamics*, 1999, 229-234

33. Melkert J.A. STRATOW first model calculation and tests. MSc thesis. Delft University of Technology, 1992

34. Nemirovsky A.S., Yudin D. *Problem Complexity and Method Efficiency in Optimization*. Wiley, New York, 1983

35. Ockels W.J. Laddermill, a novel concept to exploit the energy in the airspace. *Aircraft Design*, 2001, 4, 81-97

36. Ockels W.J. *Wind energy converter using kites*, November 12, 1996. European Patent EP084480, Dutch Patent NL1004508, Spanish Patent SP2175268, US Patent US6072245

37. Ockels W.J. *Knowledge status December 1998 and baseline Laddermill test model functional requirements*. Technical note TN-O-mill 99/01, ESA: ESTEC, 1999

38. www.ockels.nl (Wubbo Ockels. Information page on Laddermill)

39. Podgaets A.R., Ockels W.J. Three-dimensional simulation of a Laddermill. *Proceedings of the 3rd Asian Conference on Wind*, 2006, pp. 119-125

40. Podgaets A.R., Seo K., Jost B., Stuhec B. Multicriterion optimisation of a ski jump. *The Engineering of Sport 5: Proceedings of International Conference* (eds. M. Hubbard, R.D. Mehta & J.M. Pallis), 2004, Vol. 2, pp. 440-446

41. Pontryagin L.S., Boltyanskii B.G., Gamkrelidze R.V., Mischenko E.F. *Mathematical theory of optimal processes*. Moscow: PhysMathLit, 1961

42. www.psi-movi.com (Parameter Space Investigation method. Home page of the Optimal Design Theory and Methods Laboratory)

43. Pugh P.F. *Wind generator kite system*. US Patent 4486669, 1984.

44. Rundle C.V. *Tethered Rotary Kite*. US Patent 5149020, 1992

45. Sanchez G. Dynamics and control of single-line kites. *The Aeronautical Journal*, 2006, No. 9, pp. 615-621

46. Sarkar D., Modak J.M. Pareto-optimal solutions for multi-objective optimization of fed-batch bioreactors using nondominaned sorting genetic algorithm. *Chemical Engineering Science*, 205, vol. 60, pp. 481-492

47. www.sequoiaonline.com (Sequoia. Hope page of the kite wind generator company)

48. Sobol I.M., Statnikov R.B. *Choosing optimal parameters in problems with many criteria*. Moscow: Science, 1981

49. Statnikov R.B., Matusov J.B. Multicriteria Analysis in Engineering. Dordrecht/Boston/London, Kluwer Academic Publishers, 2002

50. Stevenson J.C., Alexander K.V. Circular flight kite tests: converting to standard results. *The aeronautical journal*, 2006, No. 9, pp. 605-614

51. Sobol I.M. Multidimensional integrals and method of Monte-Karlo. *Transactions of Academy of Sciences of USSR*, 1957, Vol. 114, No. 4, pp. 706-709

52. Williams P., Sgarioto D., Trivailo, P. Motion planning for an aerial-towed cable system. *AIAA Guidance, Navigation and Control Conference,* 2005, AIAA 2005-6267

53. Williams P., Lansdorp B., Ockels W. Modeling and control of a kite on a variable length flexible inelastic tether. *AIAA Guidance, navigation and control conference*, 2007 (submitted)

54. White F.M., Wolf D.F. A theory of three-dimensional parachute dynamic stability. *Journal of aircraft*, 1968, Vol. 5, No. 1, pp. 86-92

55. Zyryanov D.A. Stress-strain state investigation of a kite for wind electric station. Project report, PSTU, 2006

56. Zhou K., Ren Z. A new controller architecture for high performance, robust, adaptive and fault tolerant control. *IEEE Transactions on Automatic Control*, 2001, vol. 46, no. 10, pp. 1613-1618

57. Zemlyakov S.D., Rutkovskii V.Y., Silaev A.V. Reconfiguration of aircraft’s control systems after failure. *Automatics and Telemechanics*, 1997, No. 1, pp. 3-20