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Fujii Laboratory
Dynamics and Control of Space Infrastructure

AWEC2019

Three-Dimensional Flight Trajectories of Tethered UAV for Optimal Energy Generation

Hironori A. FUJII[1], Takumi TOMITA[2], Tairo KUSAGAYA[3], and Hiroki YAMAMOTO[3],

[1]Tokyo Metropolitan Institute of Technology,

[2] Tokyo Metropolitan University,

[3]Tokyo Metropolitan College of Industrial Technology,

TMIT (Tokyo Metropolitan Institute of Technology)

- Super tether deployed in space 132.6m as the first success in the world in 2007.
- The project is an international space demonstration by Japan, Europe, USA, and Australia.

Two types of AWE
1. Wind turbine is employed
2. No wind turbine: Wings of UAV act as blades

For examples:

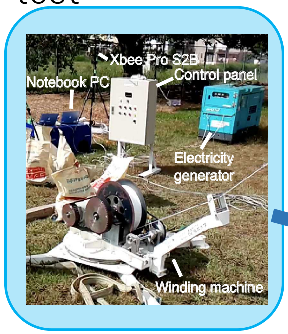
1. Makani Power, etc.

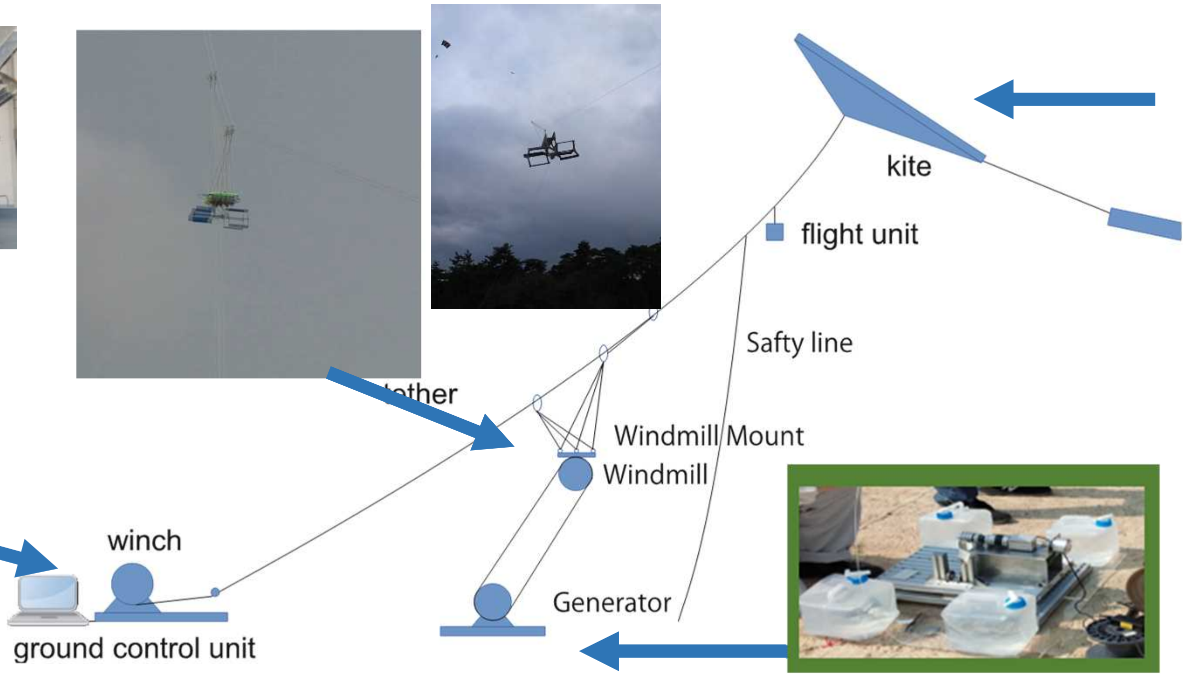
2. Ampyx Power, etc

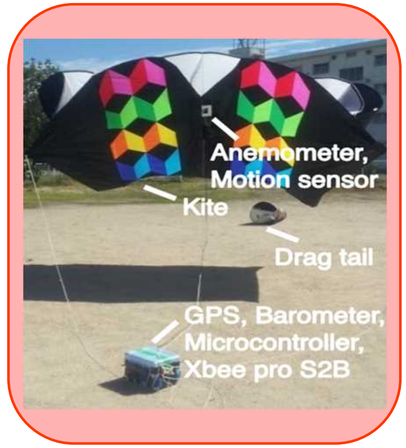
HSWG(High Sky Wind energy Generation) on tethered system

Hironori A. FUJII[1][2], Hiroshi OKUBO[3], Yasutake TAKAHASHI[4], Yusuke MARUYAMA[5]
Tairo KUSAGAYA[6], Shigeo YOSHIDA[7], Kazuo ARAKAWA[7], Hiroki ENDO[1][7],
Kenji UCHIYAMA[8], Kazuichi SEKI[9], and Takeo WATANABE[3]
[1]TMIT & Co., [2]Tokyo Metropolitan University, [3]Kanagawa Institute of Technology,
[4]University of Fukui, [5]Maeda Corporation, [6]Tokyo Metropolitan College of Industrial Technology,
[7]Kyusyu University, [8]Nihon University, [9]Tokai University

Wind tunnel test







Kite
- span:4.5m
- Chord length:2.1m
- weight:1.8kg

Windmill
・0.6m*0.6m*2 (6kW)

Vertical-Axis wind turbine is lifted by UAV.

Magnus effect is expected to help the augmentation of lift as in many projects for employment of the vertical-axis wind turbine.

The study is in a preliminary step looking for any fund to change the study into a projective one.

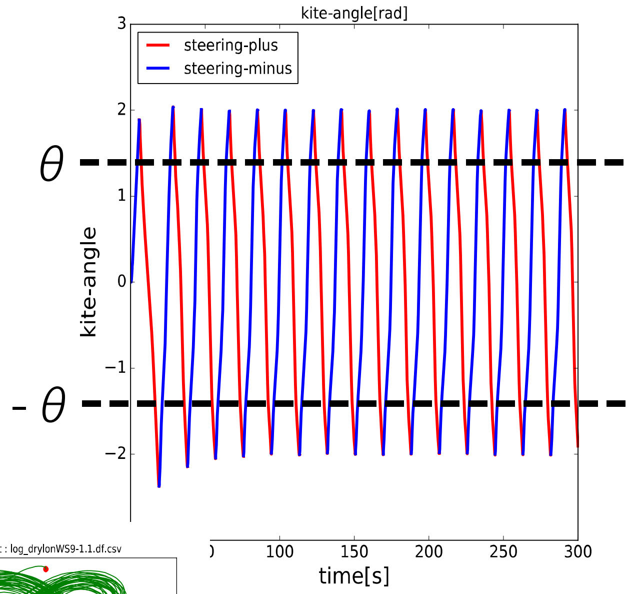
Fundamental elements of AWE technology:

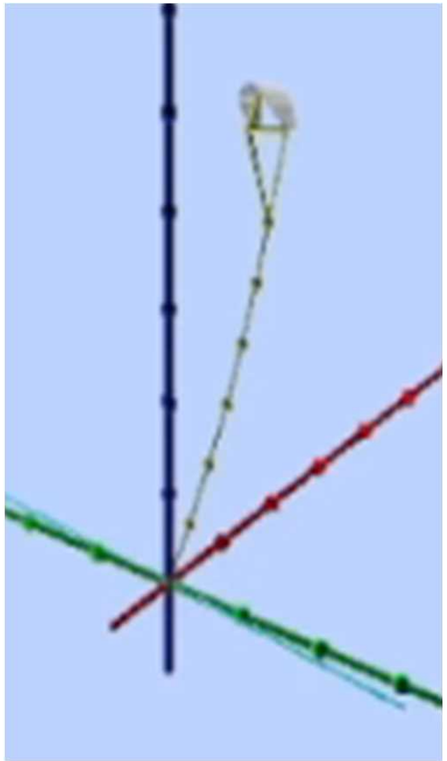
1. Lifting of wind turbine
2. Effective energy transfer
3. Improvement of performance
1. Safety issue for Japanese original size of AWE > 100kw

Kite Flight based on Hysteresis Control

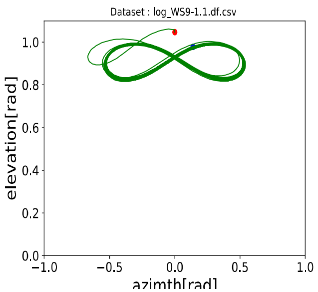
- **Masafumi Narikawa and Yasutake Takahashi, University of Fukui, Japan**

- **Steering is turned clockwise (blue line), the attitude angle of the kite increases.**
- **Switch steering operation if the attitude angle exceeds the threshold θ or become less than $-\theta$.**

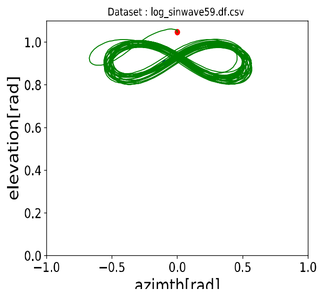




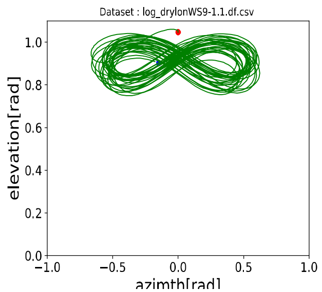
base wind speed 9m/s



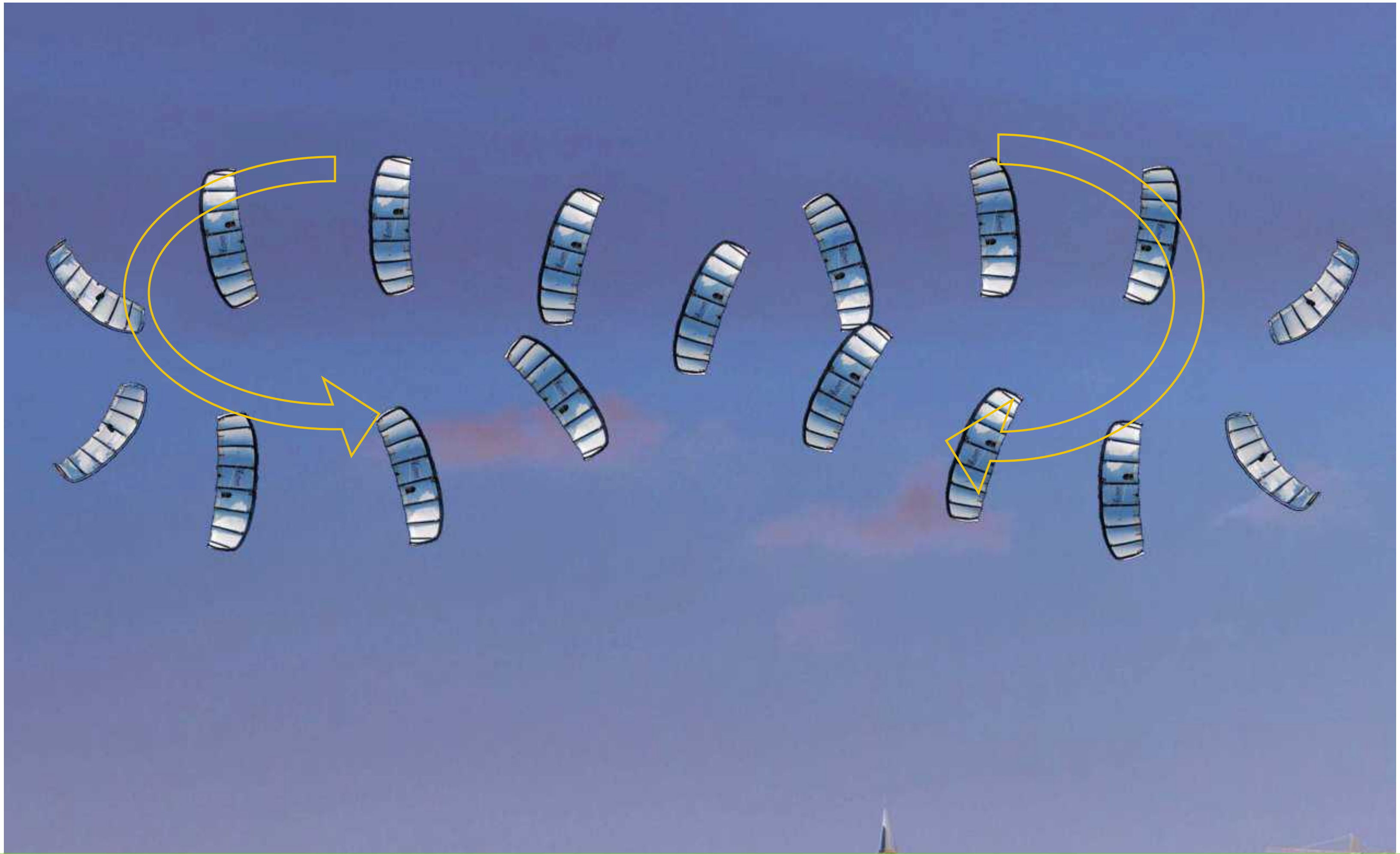
No wind disturbance



Sine wave



Dryden model

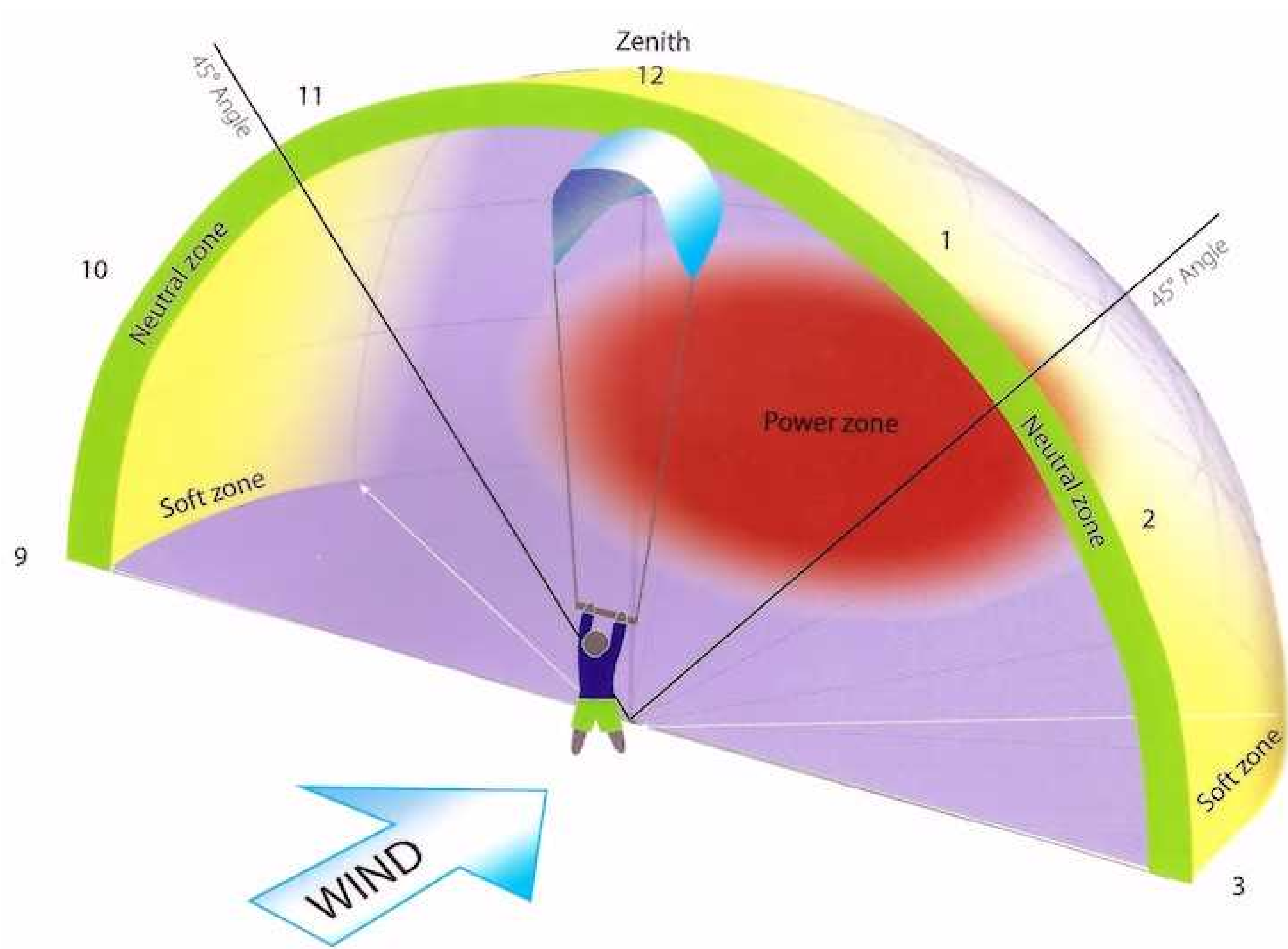


altitude（120m） → wind velocity 1.6

Closed trajectory → wind velocity 2～3

both

Wind velocity3～5 → wind energy 27～125



Windows of wind

Three-Dimensional Flight Trajectories of Tethered UAV for Optimal Power Production

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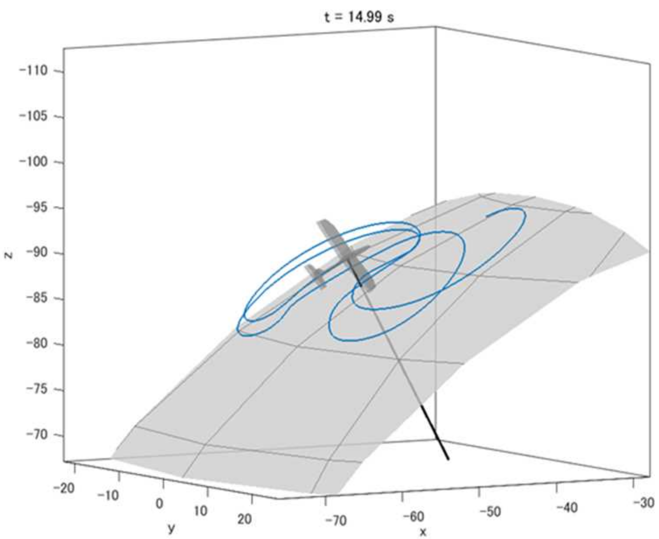


Fig.3(a) 2D periodic orbit (Many turns in deployment followed by a decent)

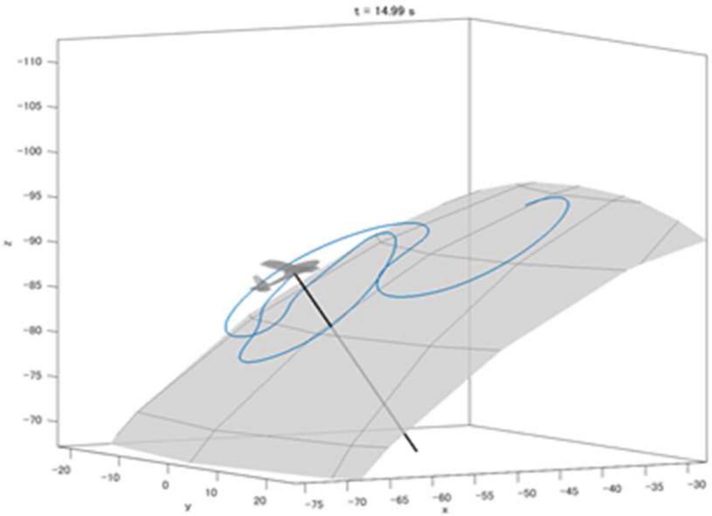


Fig.3(b) 3D One periodic orbit (Large-Deployment-Return in one turn)

<u>Paul Williams, Bas Lansdorp,T and Wubbo Ockels、</u> “Optimal Crosswind Towing and Power Generation with Tethered Kites,” Journal of Guidance, Control, and Dynamics, Vol. 31, No. 1, January-February 2008

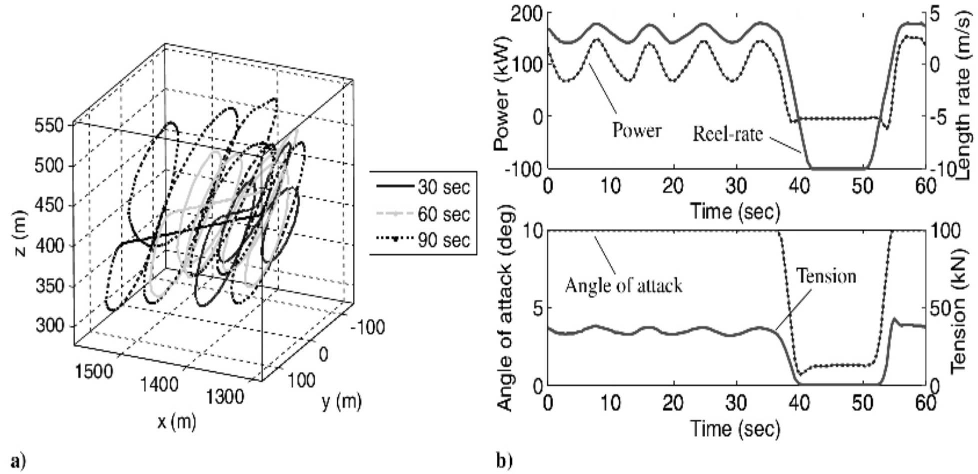
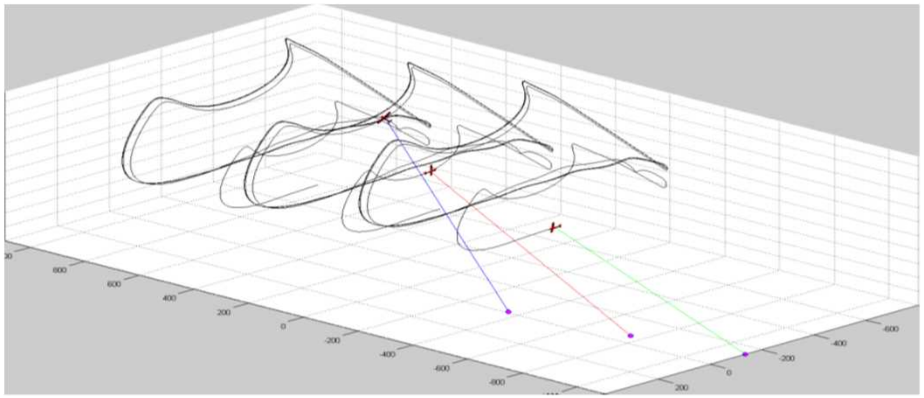


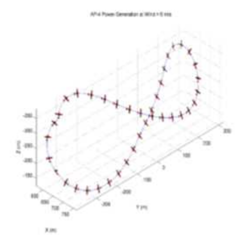
Fig. 11 Optimal power-generating kite trajectories: a) examples with 30-, 60-, and 90-s periods and b) example of power generation for a cycle time of

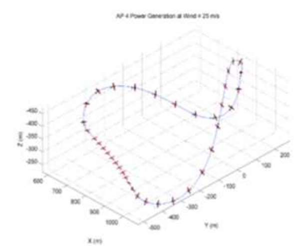
<u>M.S.Jerez Venegas</u>, Path Optimizationof Pumping Kite System、Delft University of Technology 2017

Ampyx Power Public Summary The Sea-Air-Farm Project

Demonstrating the potential of far offshore floating airborne wind farms



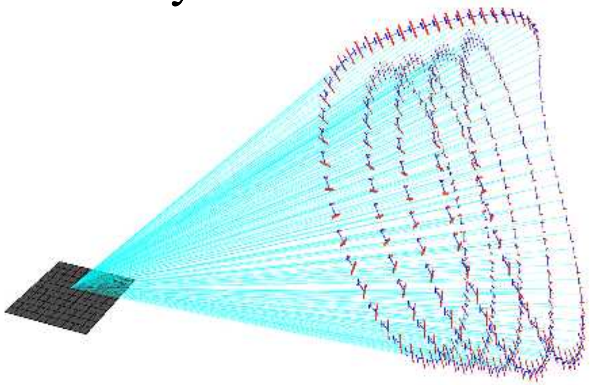


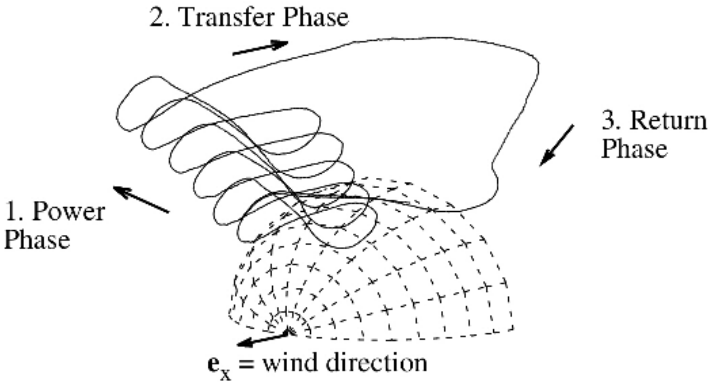


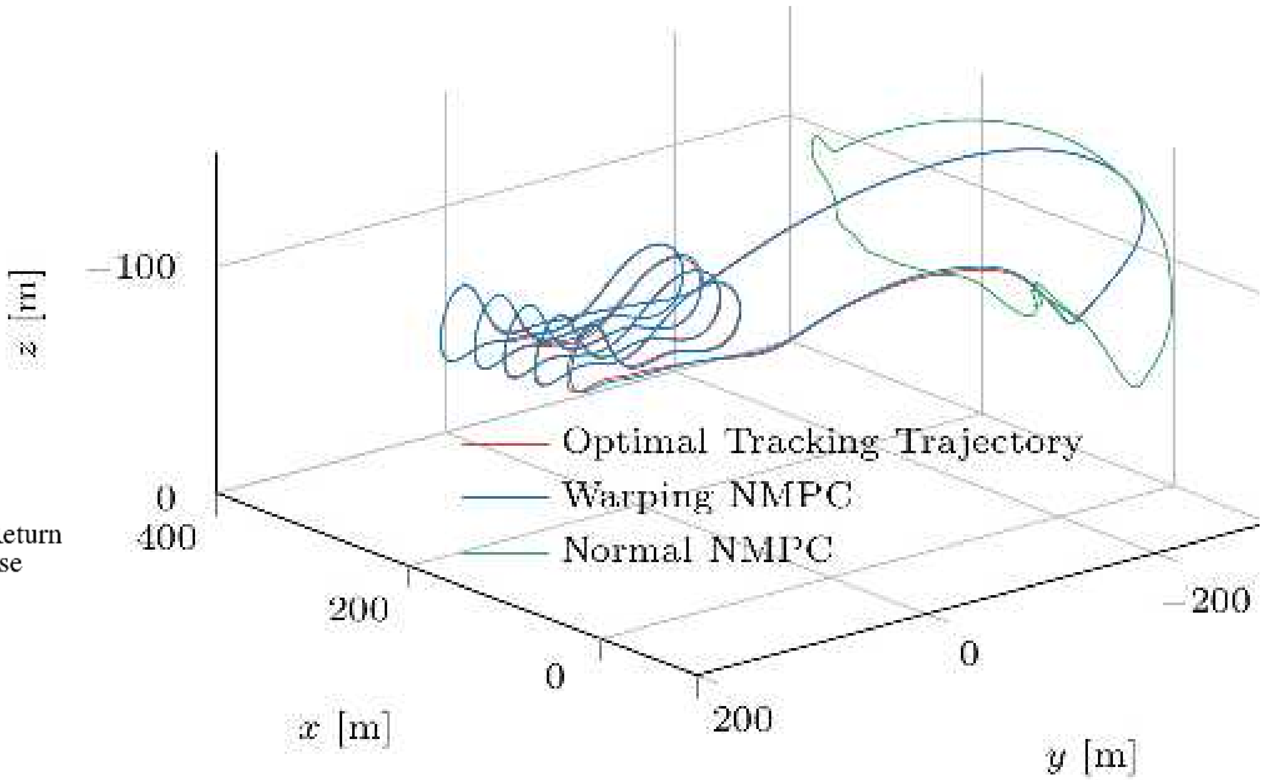
Greg Horn, S ´ ebastien Gros, Moritz Diehl, Numerical Trajectory Optimization for AirborneWind Energy Systems Described by High Fidelity Aircraft Models

Jesus Lago, Michael Erhard, Moritz Diehl, “Warping NMPC for Online Generation and Tracking of Optimal Trajectories,” IFAC PapersOnLine 50-1 (2017) 13252-13257

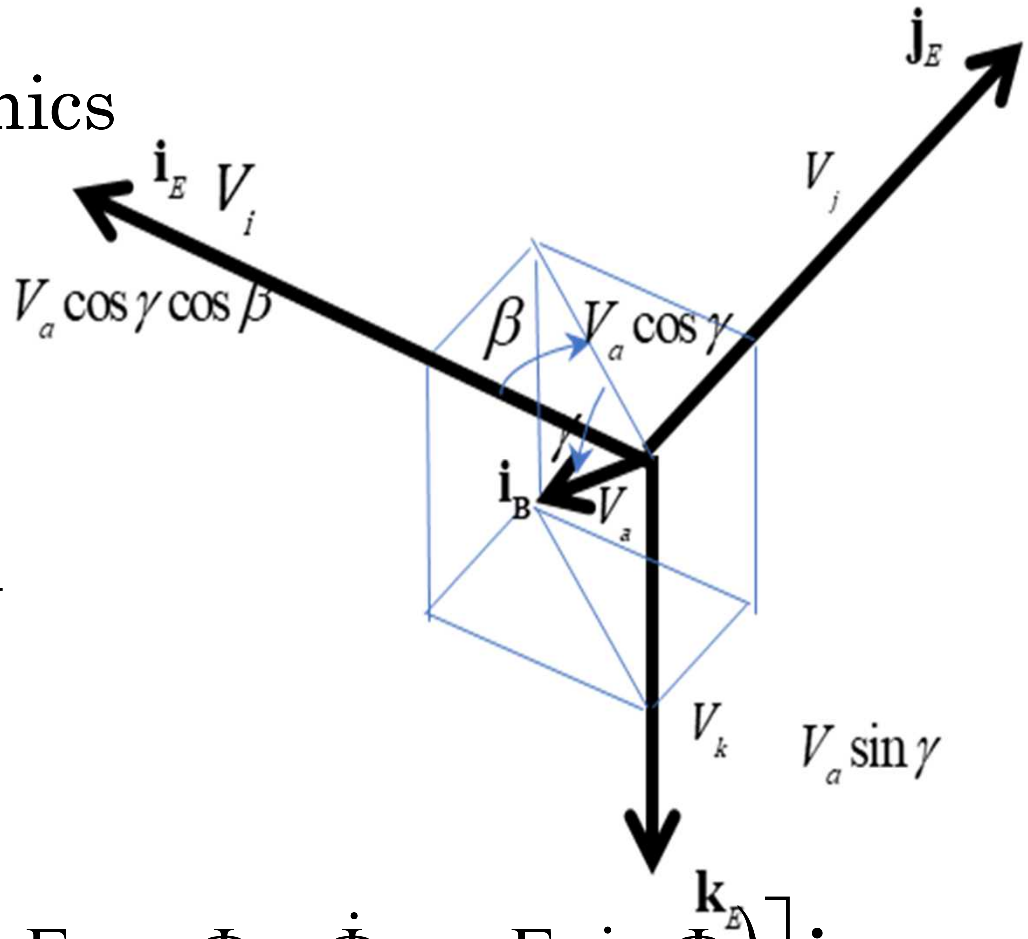
Michael Erhard, Hans Strauch, Flight control of tethered kites in autonomous pumping cycles for airborne wind energy, SkySails GmbH, Luisenweg 40, D-20537 Hamburg, Germany







A particle in 3D dynamics



Wind axes defined
as body axes of UAV

$$\mathbf{V_a} := V_a \mathbf{i_B} = \left[W_0 + \ell \left(\dot{\Gamma} \sin\Gamma \cos\Phi + \dot{\Phi} \cos\Gamma \sin\Phi \right) \right] \mathbf{i}_E$$

$$+ \ell \left(\dot{\Gamma} \sin\Gamma \sin\Phi - \dot{\Phi} \cos\Gamma \cos\Phi \right) \mathbf{j}_E - \ell \dot{\Gamma} \cos\Gamma \mathbf{k}_E$$

$$\mathbf{V_a} := V_i \mathbf{i}_E + V_j \mathbf{j}_E + V_k \mathbf{k}_E \quad (2)$$

Equations of motion

T ：Tether tension

$$m\dot{V}_a + (1/2)\rho C_D S V_a^2 - mg\sin\gamma$$

$$+T\left[\left(\frac{x}{\ell}\cos\beta + \frac{y}{\ell}\sin\beta\right)\cos\gamma + \frac{z}{\ell}\sin\gamma\right] = 0$$

＊Vertical plane flight direction

$$mV_a\dot{\beta}\cos\gamma - (1/2)\rho C_L S V_a^2 \sin\varphi - T\left(\frac{x}{\ell}\sin\beta - \frac{y}{\ell}\cos\beta\right) = 0$$

＊Horizontal plane

$$mV_a\dot{\gamma} - mg\cos\gamma + (1/2)\rho C_L S V_a^2 \cos\varphi$$

$$-T\left[\sin\gamma\left(\frac{x}{\ell}\cos\beta + \frac{y}{\ell}\sin\beta\right) - \frac{z}{\ell}\cos\gamma\right] = 0$$

＊Vertical direction

For flight tangent to a sphere

$$x\left(V_i - W_0\right) + yV_j + zV_k = 0$$

$$m\dot{V}_a + (1/2)\rho C_D V_a^2 - mg\sin\gamma = T\frac{W_0}{V_a}\frac{x}{\ell}$$

Thrust

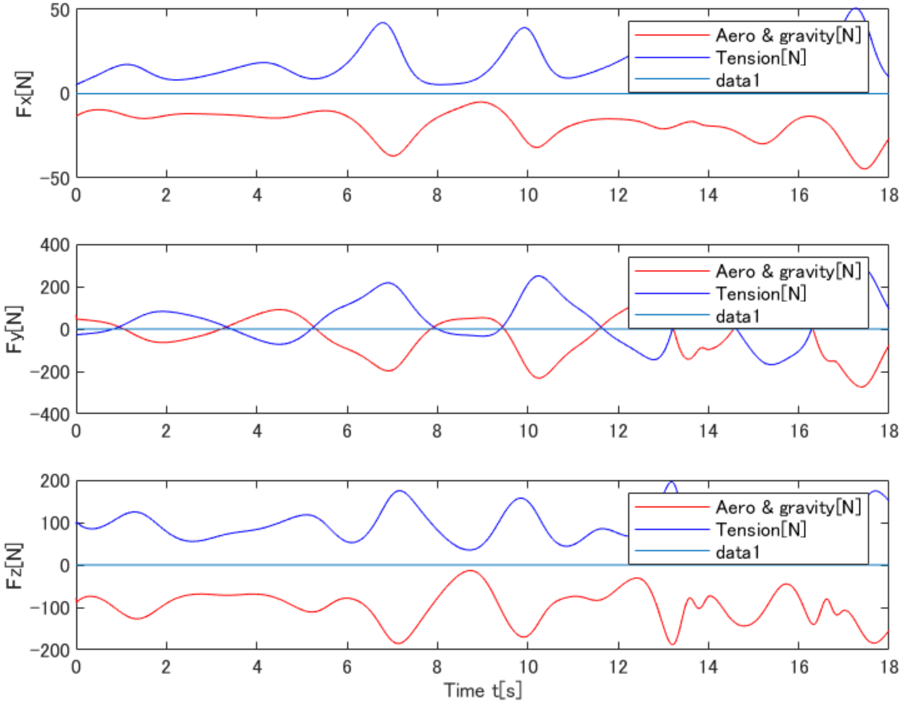
$$mV_a\dot{\beta}\cos\gamma - (1/2)\rho C_L V_a^2 \sin\varphi = T\frac{\left(x\sin\gamma - y\cos\gamma\right)}{\ell}$$

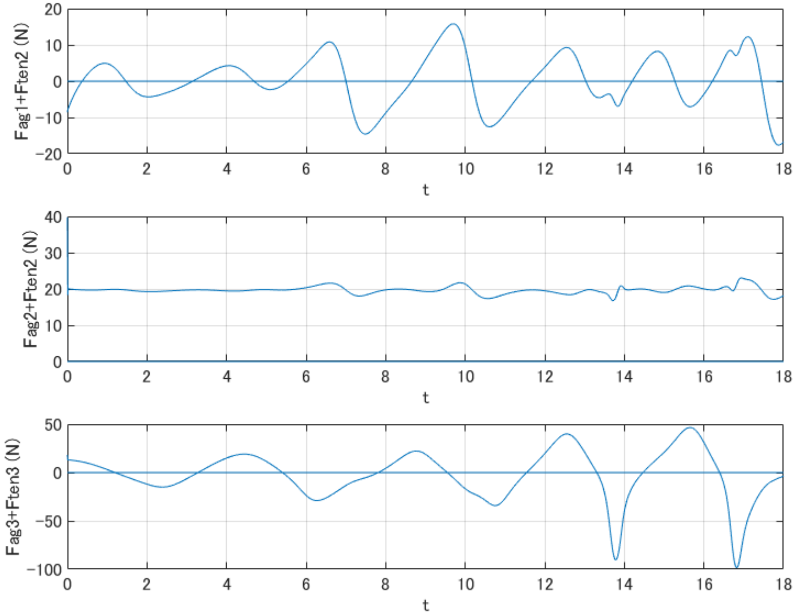
Side force by tether

$$mV_a\dot{\gamma} + (1/2)\rho C_L V_a^2 \cos\varphi - mg\cos\gamma = T\frac{1}{\cos\gamma}\left(\frac{W_0\sin\gamma}{V_a}\frac{x}{\ell} - \frac{z}{\ell}\right)$$

Vertical force by tether

Turn performance Nonlinear compensation for roll





Left: Aerodynamic force and tension
Right: combined force
From top to bottom: Flight direction. Horizontal and vertical plane

Tether tension assists thrust of flight

$$m\dot{V}_a + (1/2)\rho C_D V_a^2 - mg\sin\gamma = T\frac{W_0}{V_a}\frac{x}{\ell} \qquad \dot{V}_a = 0 \quad \Rightarrow$$

After some manipulations

$$V_{a\max} = \sqrt[3]{\frac{TW_0x}{\rho C_D\ell} + \sqrt{\left(\frac{TW_0x}{\rho C_D\ell}\right)^2 - \frac{8}{27}\left(\frac{mg\sin\gamma}{\rho C_D}\right)^3}} + \sqrt[3]{\frac{TW_0x}{\rho C_D\ell} - \sqrt{\left(\frac{TW_0x}{\rho C_D\ell}\right)^2 - \frac{8}{27}\left(\frac{mg\sin\gamma}{\rho C_D}\right)^3}}$$

$$T = |\mathbf{L}+\mathbf{D}| = \sqrt{L^2 + D^2} = (1/2)\rho\sqrt{C_L^2 + C_D^2}\,V_a^2 = (1/2)\rho C_D\sqrt{1+(C_L/C_D)^2}\,V_a^2$$

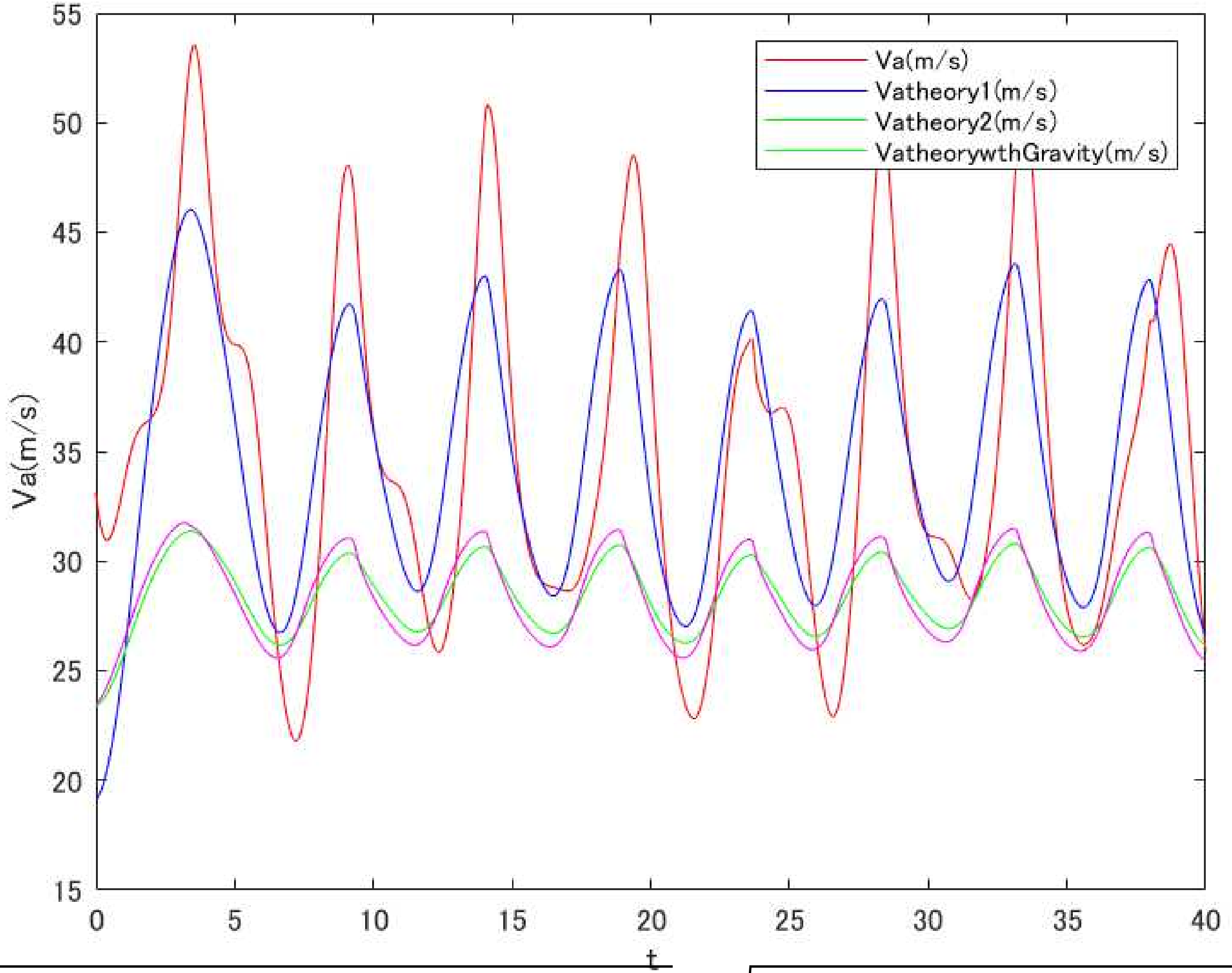
$$m = 0 \Rightarrow$$

$$\frac{V_a}{W_0} = \sqrt{1+(C_L/C_D)^2}\,\frac{x}{\ell} \simeq \frac{C_L}{C_D}\sqrt{1+\left(\frac{C_D}{C_L}\right)^2}\,\frac{x}{\ell} \simeq \frac{C_L}{C_D}\left[1+\frac{1}{2}\left(\frac{C_D}{C_L}\right)^2\right]\frac{x}{\ell}$$

$$C_D/C_L << 1 \quad \Rightarrow$$

$$v_a \simeq v_{k,c} = (v_w - v_{out})\frac{C_L}{C_D}$$

Loyd, M. L.: Crosswind kite power. Journal of Energy 4(3), 106–111 (1980).



$$V_{a\max} = \sqrt[3]{\frac{TW_0 x}{\rho C_D \ell} + \sqrt{\left(\frac{TW_0 x}{\rho C_D \ell}\right)^2 - \frac{8}{27}\left(\frac{mg\sin\gamma}{\rho C_D}\right)^3}} + \sqrt[3]{\frac{TW_0 x}{\rho C_D \ell} - \sqrt{\left(\frac{TW_0 x}{\rho C_D \ell}\right)^2 - \frac{8}{27}\left(\frac{mg\sin\gamma}{\rho C_D}\right)^3}}$$

Time response of flight velocity (wind speed 6m/s, L/D = 14)

Model of UAV：A120RC

Weight 500g, length 580mm, span 1200mm, Aspect ratio = 7.4,

Wing area：$S = 0.1936 m^2$, Lift coef. gradient：$C_{L\alpha} = 5.26$ /rad.,

Drag:$Cd = Cd_0 + C_L/(\pi e AR)$, $Cd_0 = 0.0069$, $e = 0.72$, , $C_L/C_d = 14$

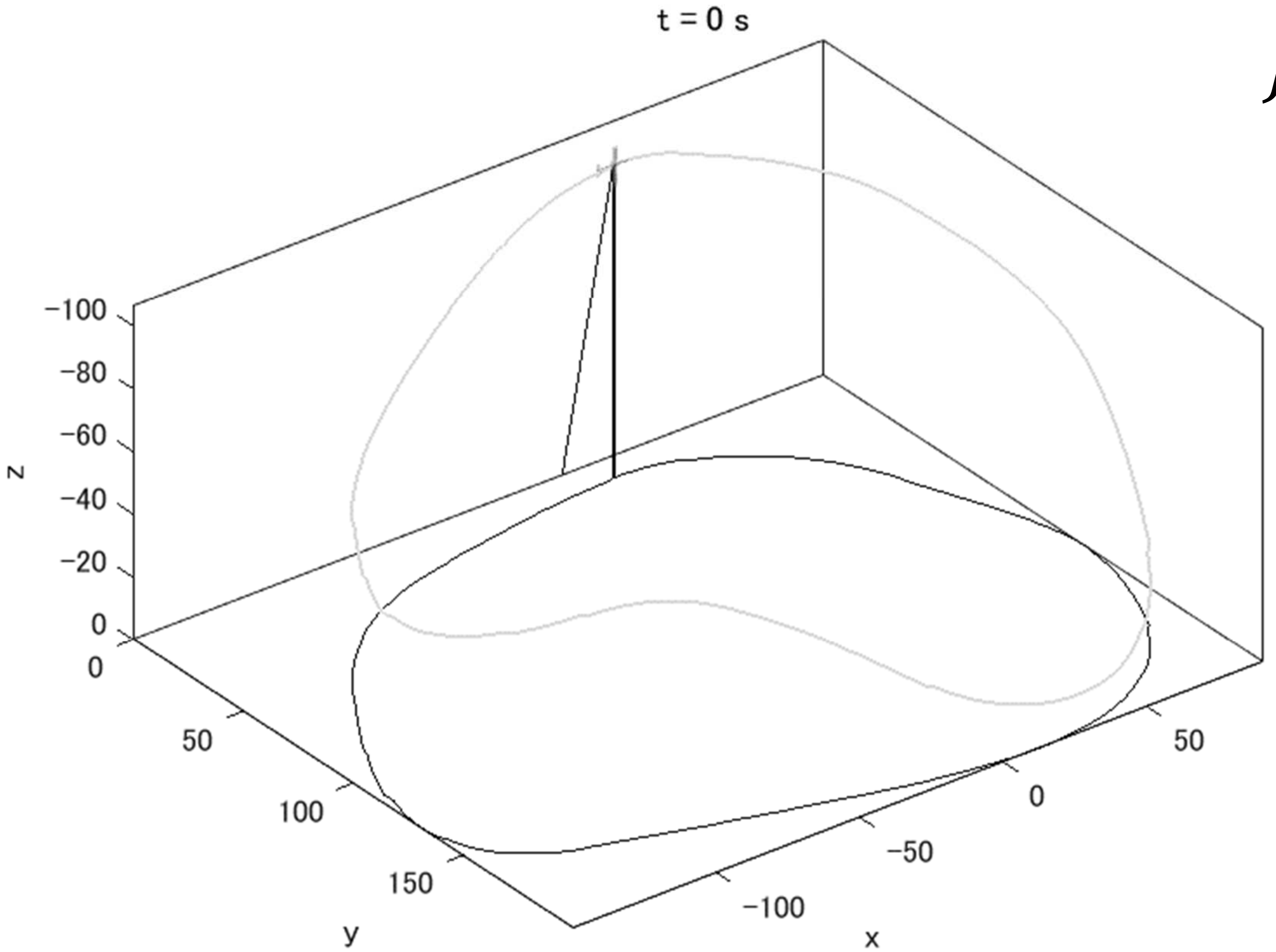
Optimal periodic trajectory of UAV (Control input: CL and bank angle) (x0=y0=10m, z0=100m)

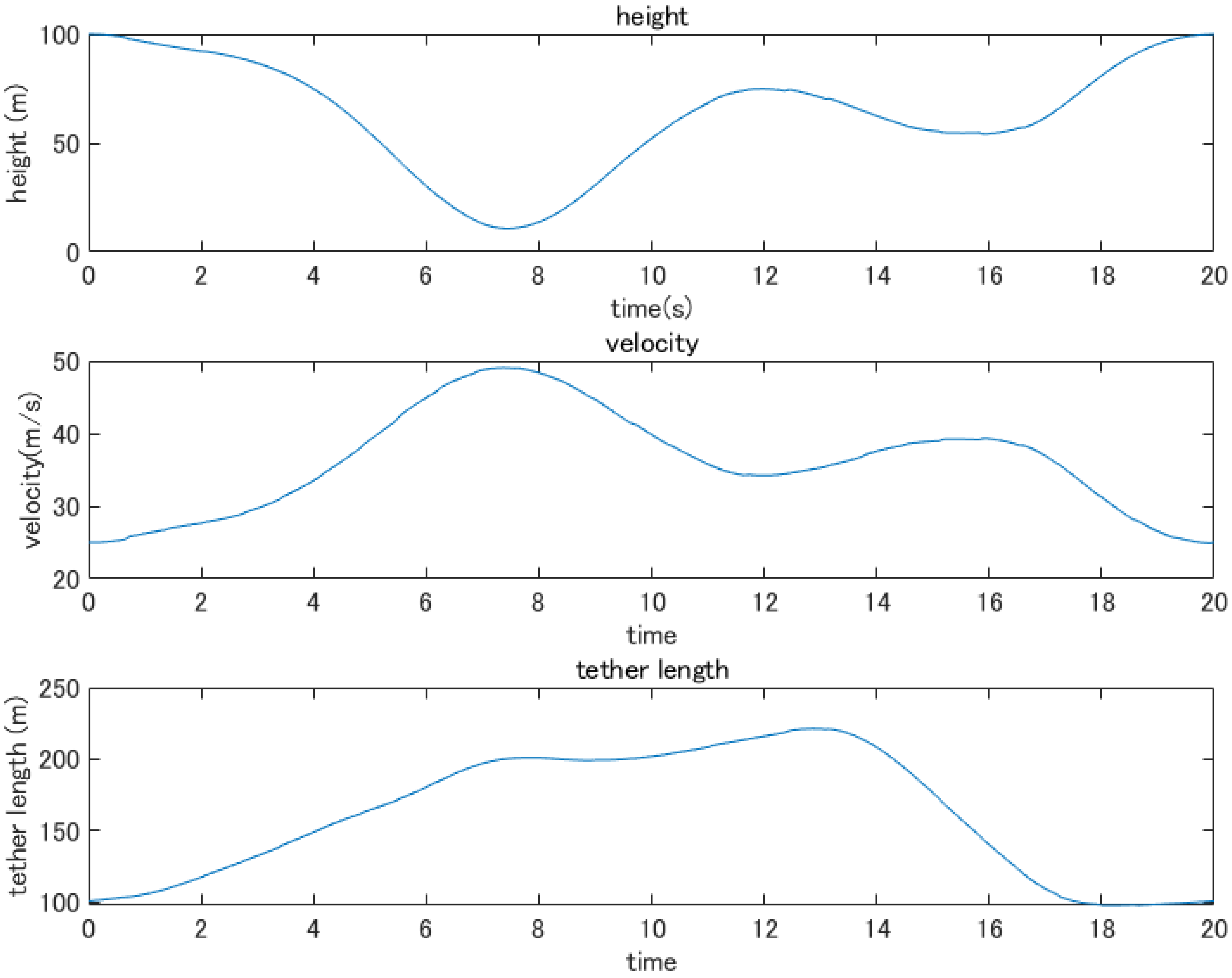
Performance index Without turbine Power:

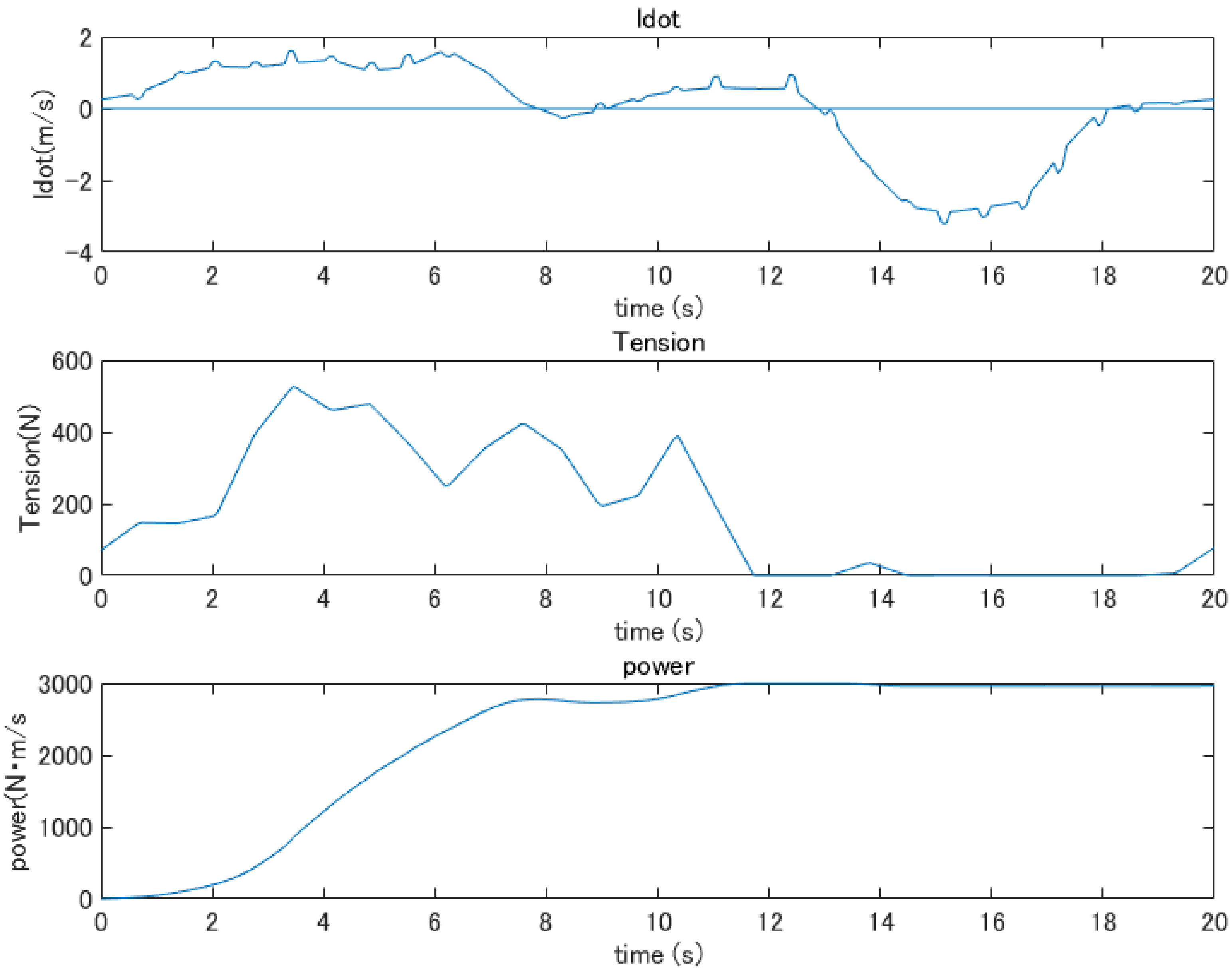
$$J = \int_{t_0}^{t_f} T \dot{\ell} \, dt$$

T: tension

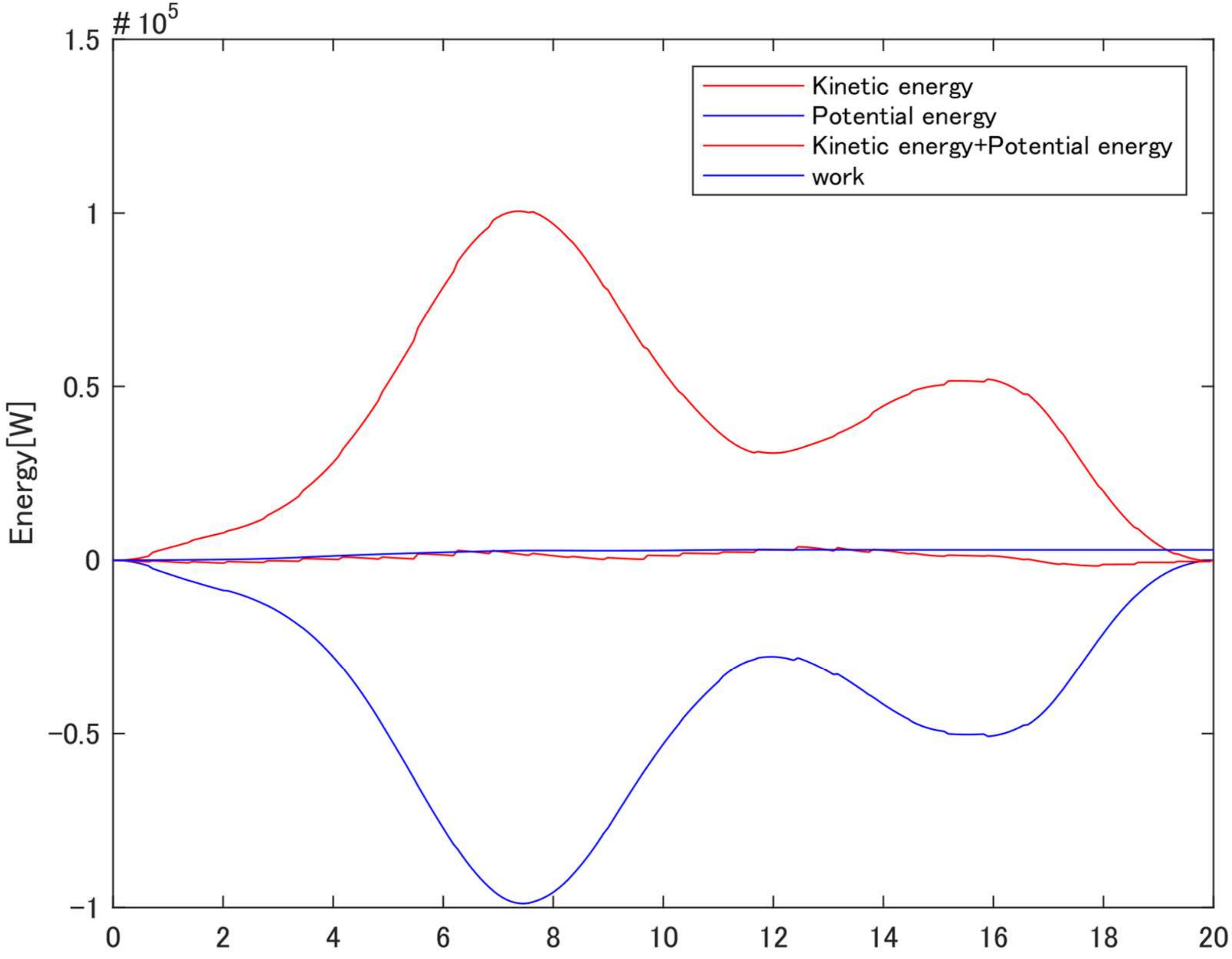
$\dot{\ell}$: deployment velocity




height
height (m)
100
50
0
0
2
4
6
8
10
12
14
16
18
20
time(s)
velocity
velocity(m/s)
50
40
30
20
time
tether length
tether length (m)
250
200
150
100
time



Performance index　Without turbine



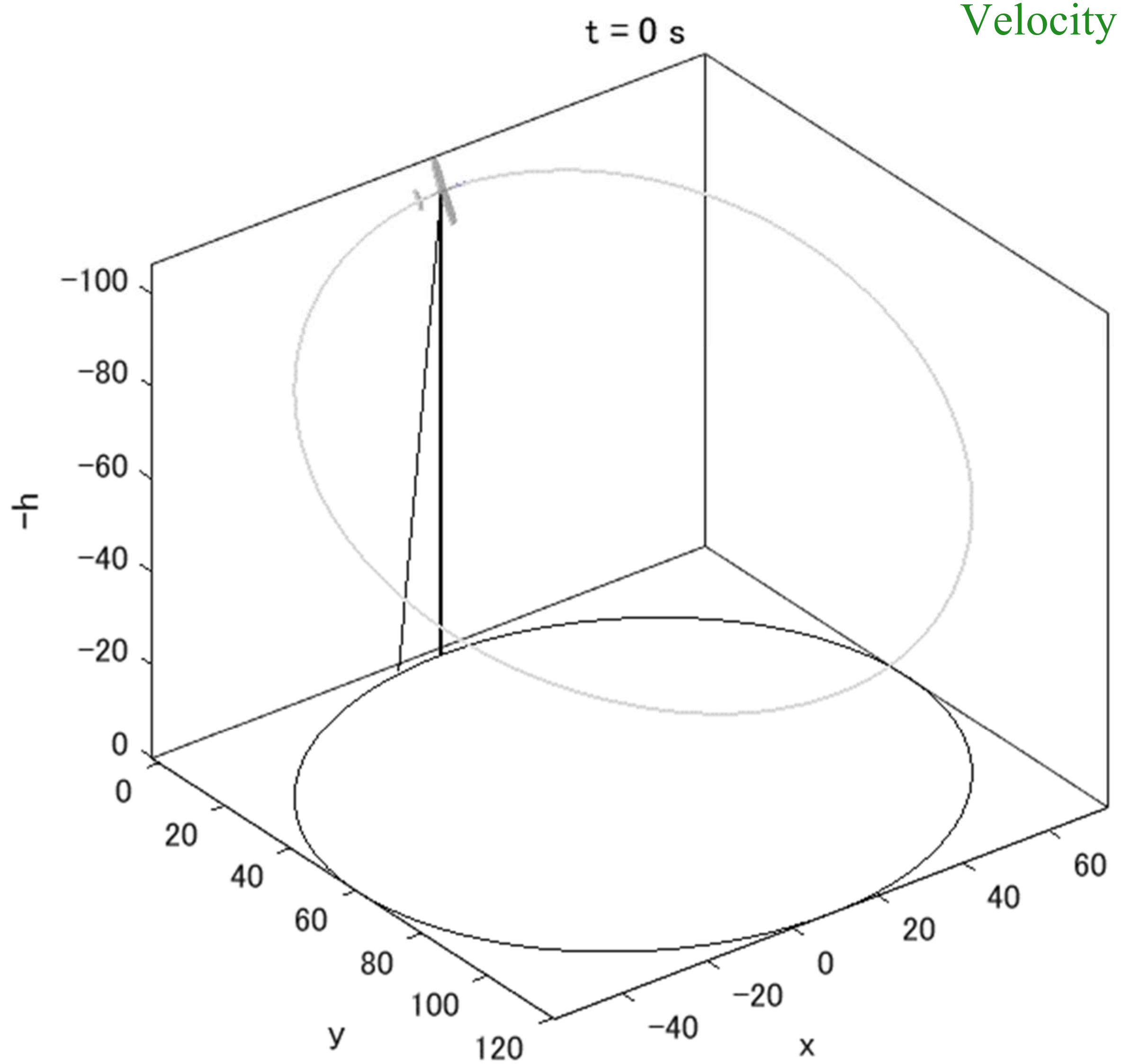
10^5
1.5
1
0.5
0
−0.5
−1
Energy[W]
0
2
4
6
8
10
12
14
16
18
20
Kinetic energy
Potential energy
Kinetic energy+Potential energy
work

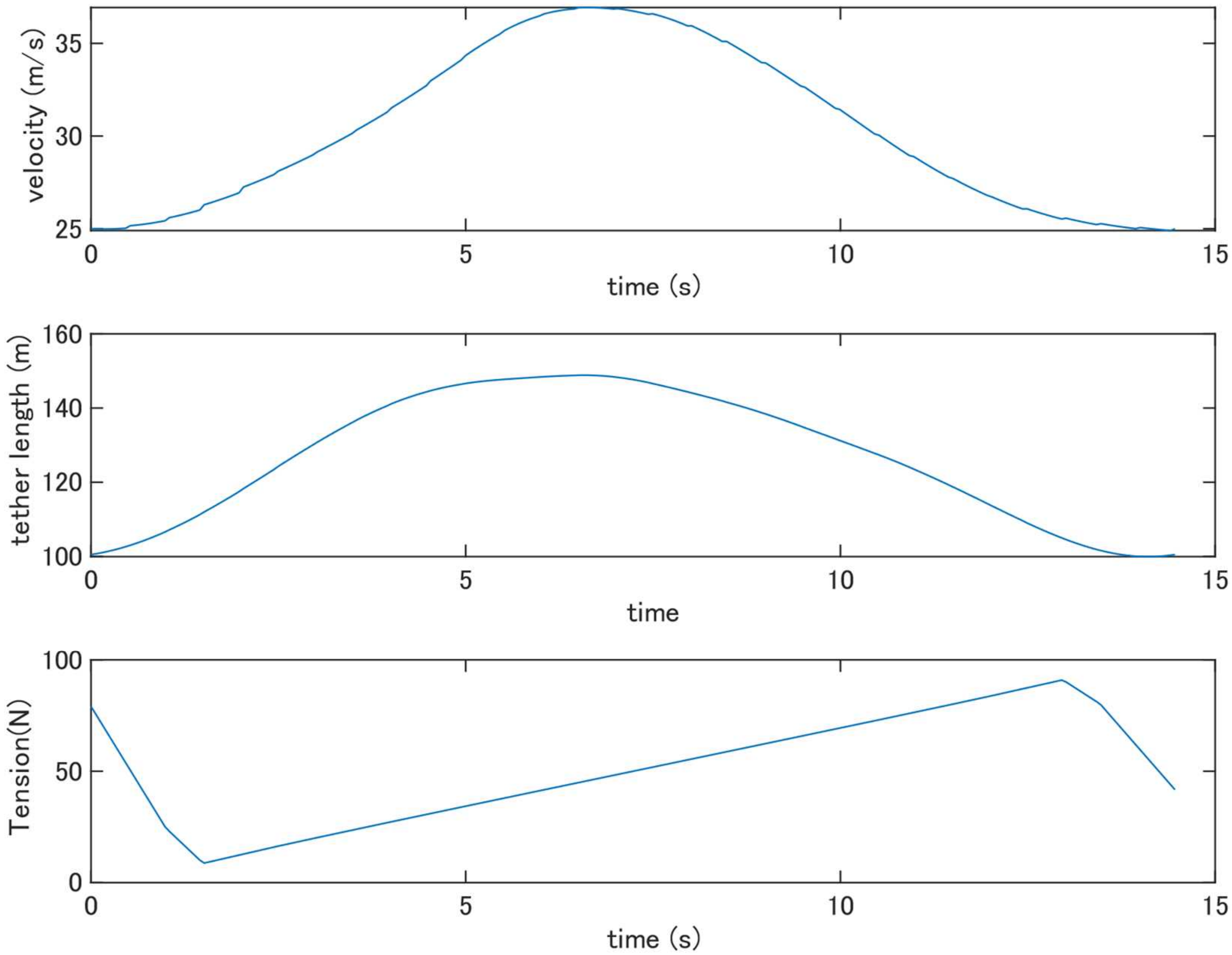
Optimal periodic trajectory of UAV (Control input: CL and bank angle) (x0=10m, y0=0m, z0=100m)

Performance index Velocity With turbine

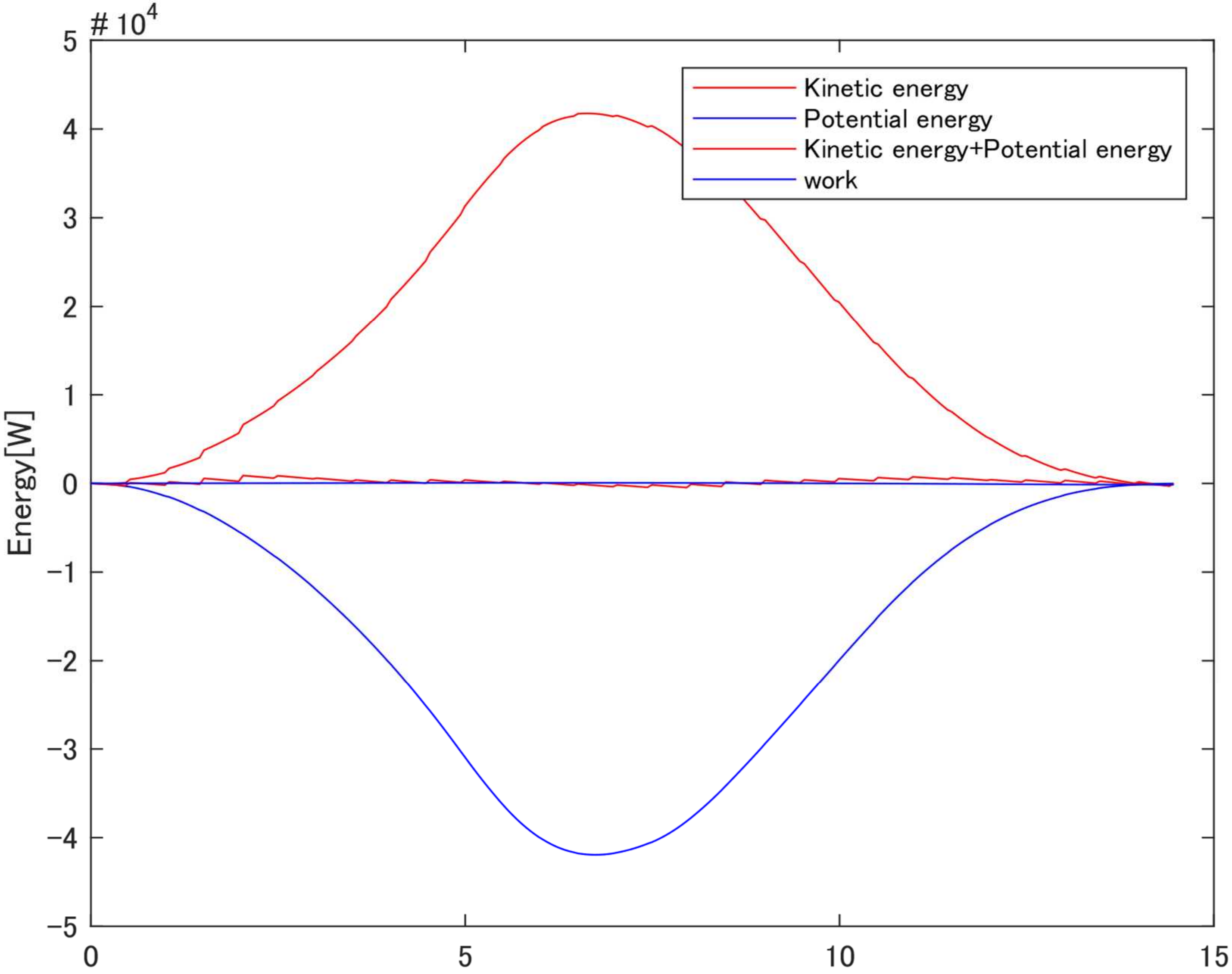
$$J = \int_{t_0}^{t_f} V_a dt$$

Maximum Tension < 100N





velocity (m/s)
35
30
25
0
5
10
15
time (s)
tether length (m)
160
140
120
100
0
5
10
15
time
Tension(N)
100
50
0
0
5
10
15
time (s)

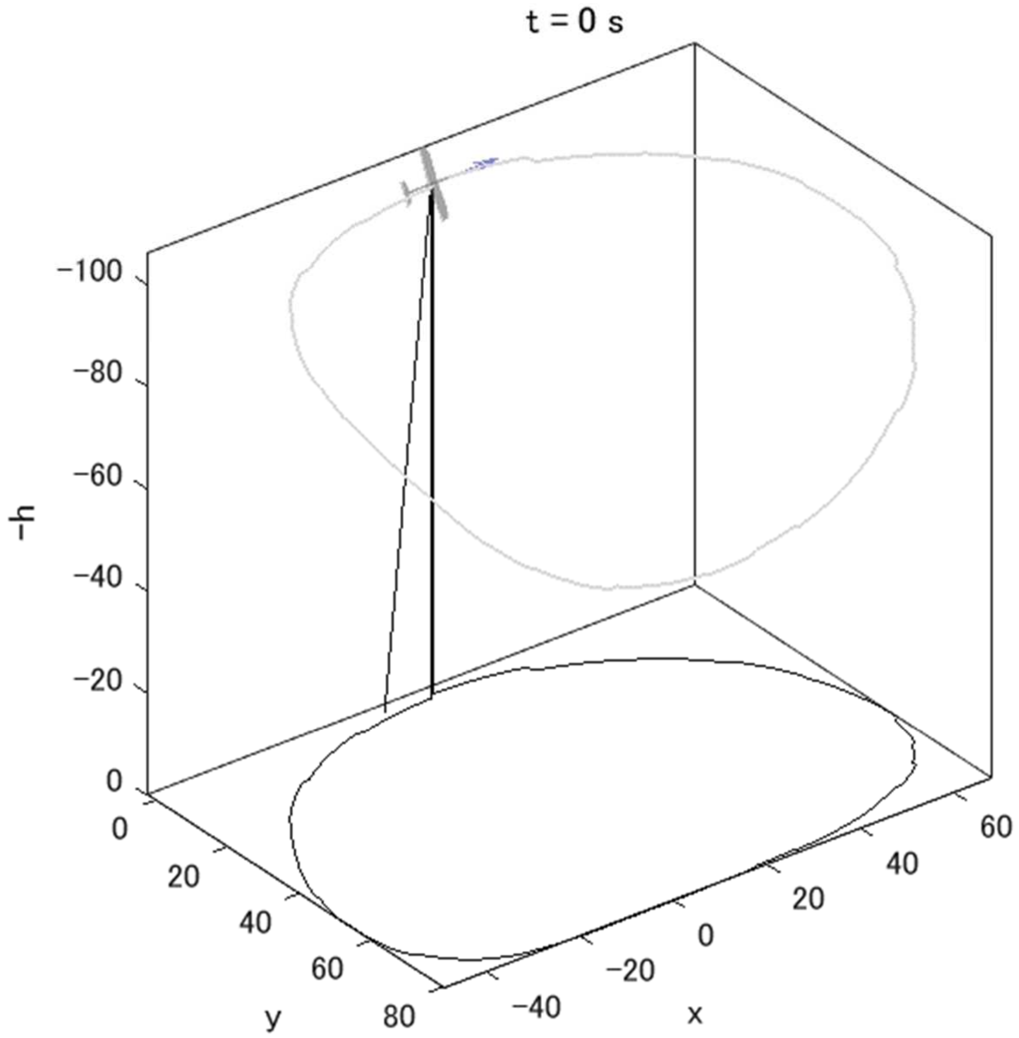


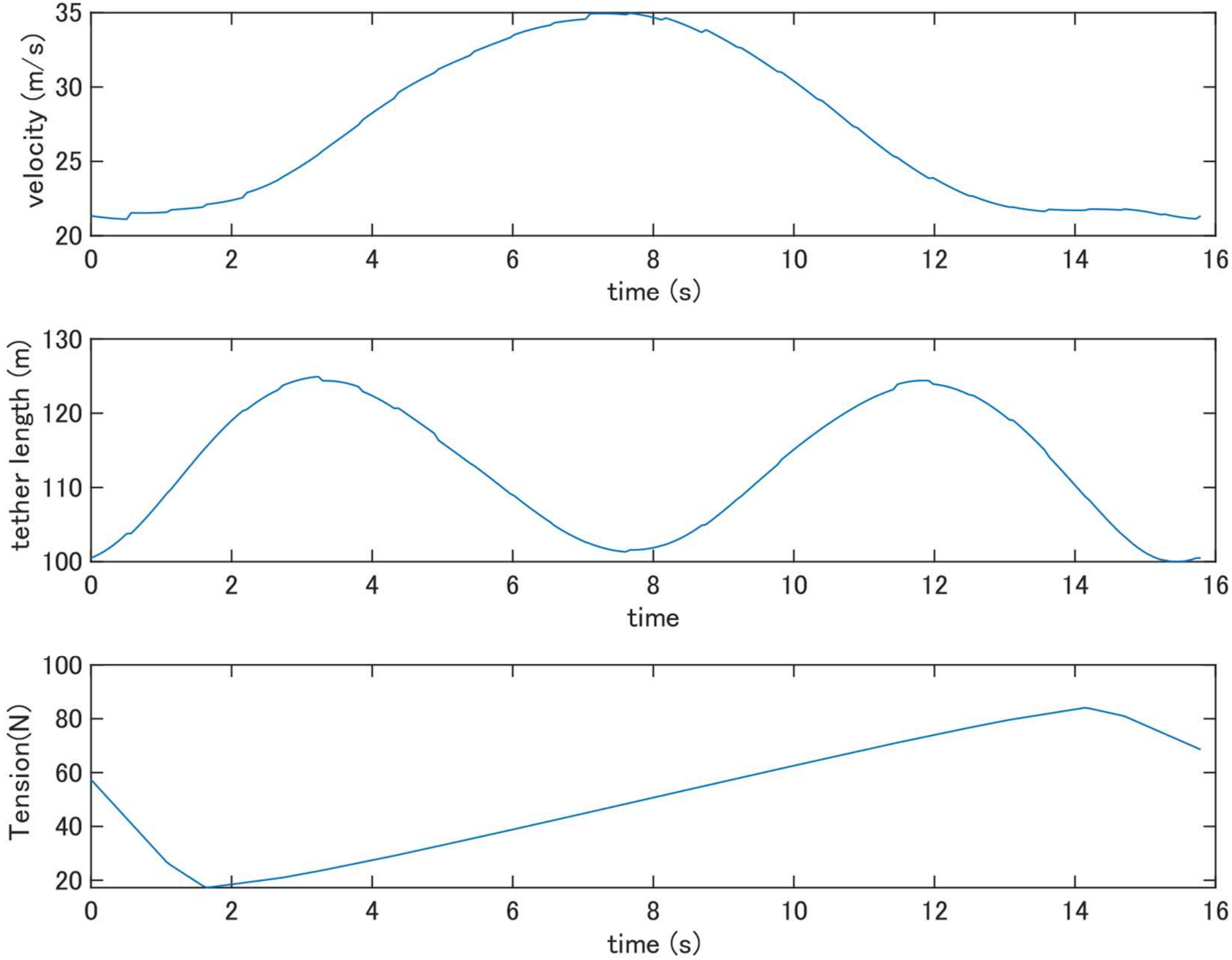
10^4
Energy[W]
Kinetic energy
Potential energy
Kinetic energy+Potential energy
work
5
4
3
2
1
0
−1
−2
−3
−4
−5
0
5
10
15

Optimal periodic trajectory of UAV (Control input: CL and bank angle) (x0=10m, y0=0m, z0=100m)

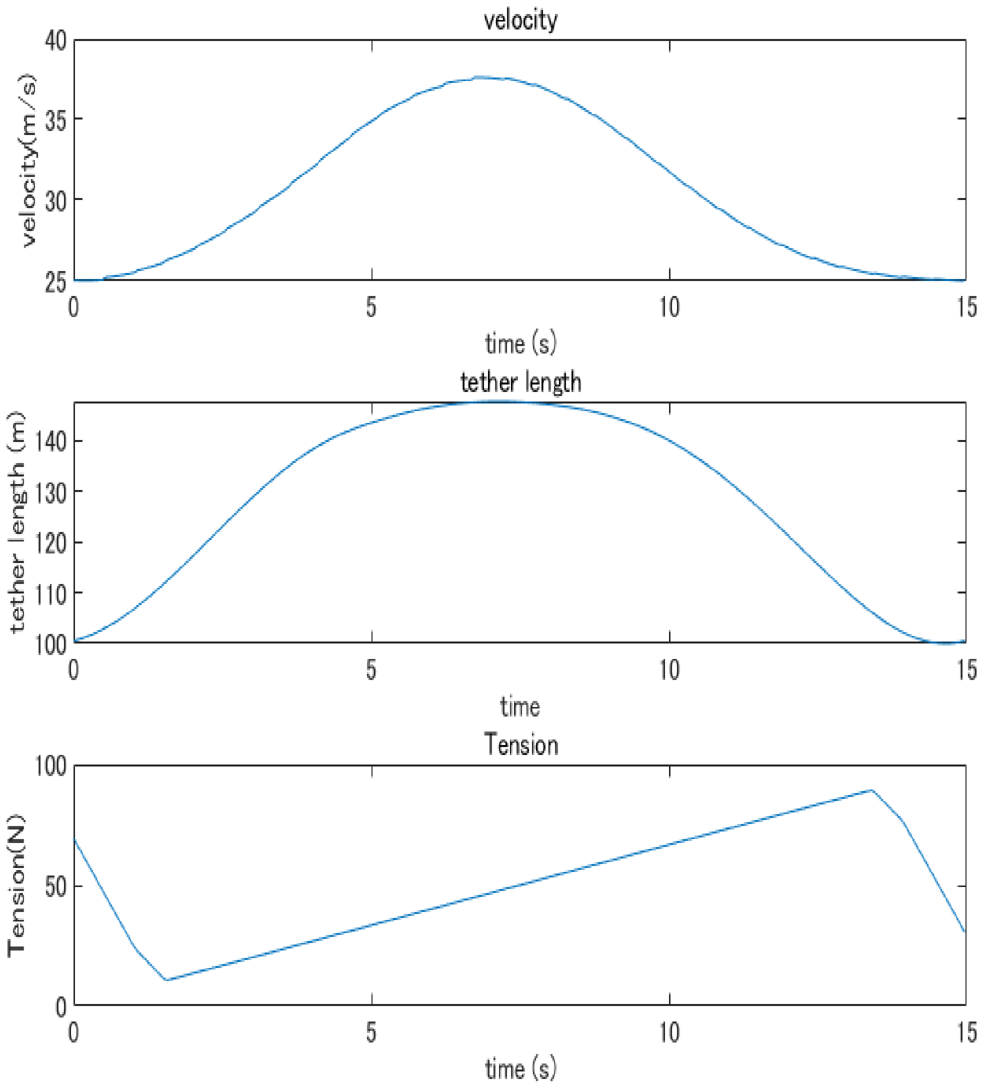
$Cd = 0.0013 * 4, CL / Cd = 14 / 4 = 3.5$

$$J = \int_{t_0}^{t_f} V_a dt$$

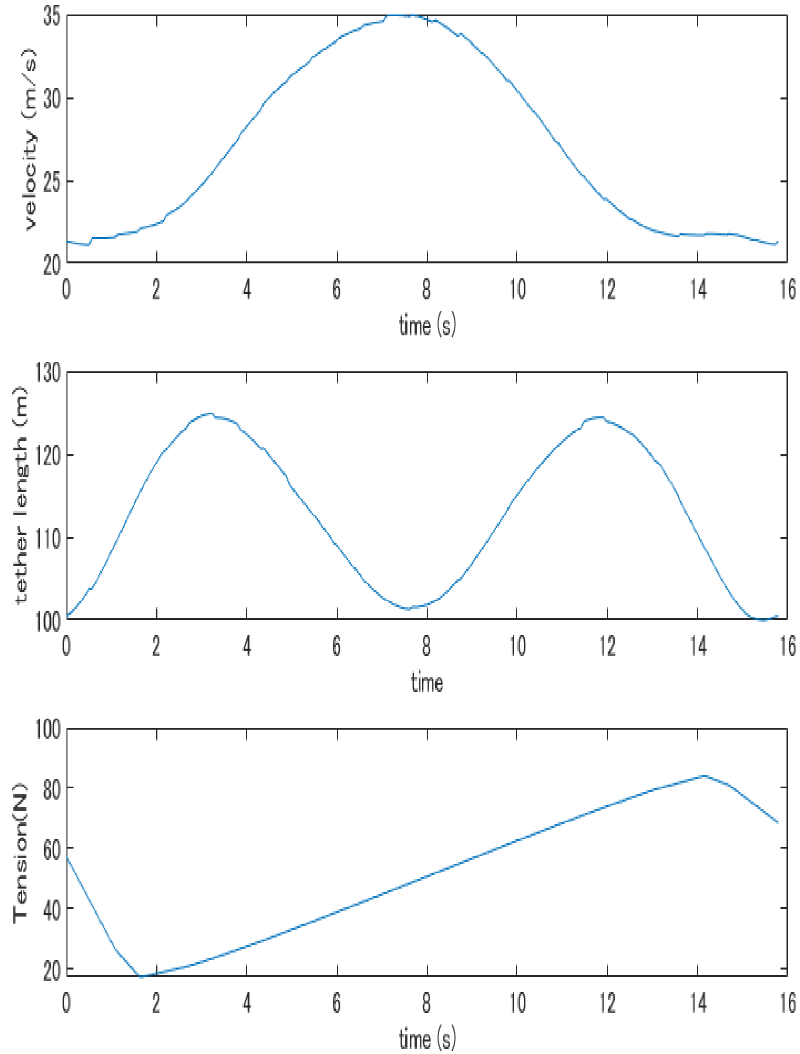




velocity (m/s)
35
30
25
20
0
2
4
6
8
10
12
14
16
time (s)
tether length (m)
130
120
110
100
time
Tension(N)
100
80
60
40
20
time (s)



$Cd = 0.0013, CL / C\mathrm{d} = 14$



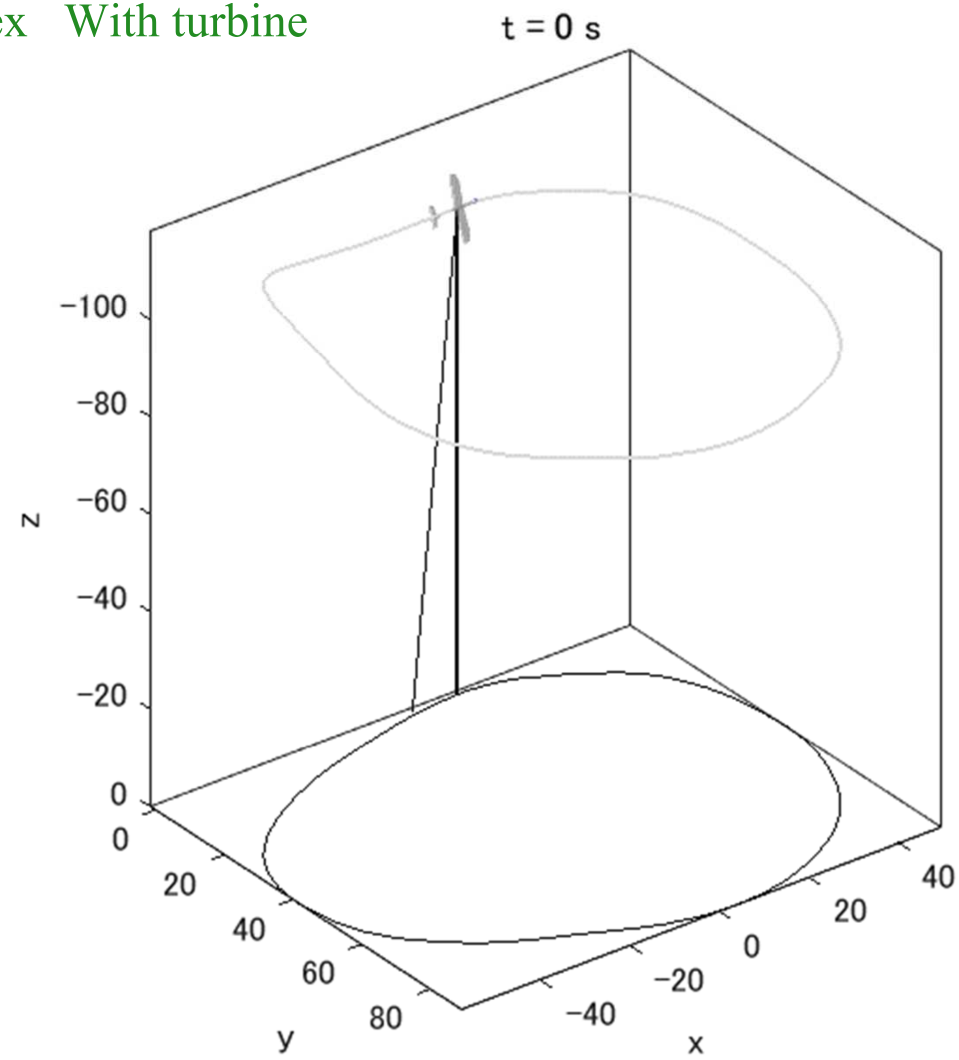
$Cd = 0.0013 * 4, CL / C\mathrm{d} = 14 / 4 = 3.5$

Optimal periodic trajectory of UAV (Control input: CL and bank angle) (x0=10m, y0=0m, z0=100m)

$Cd = 0.0013 * 4, CL / Cd = 14 / 4 = 3.5$

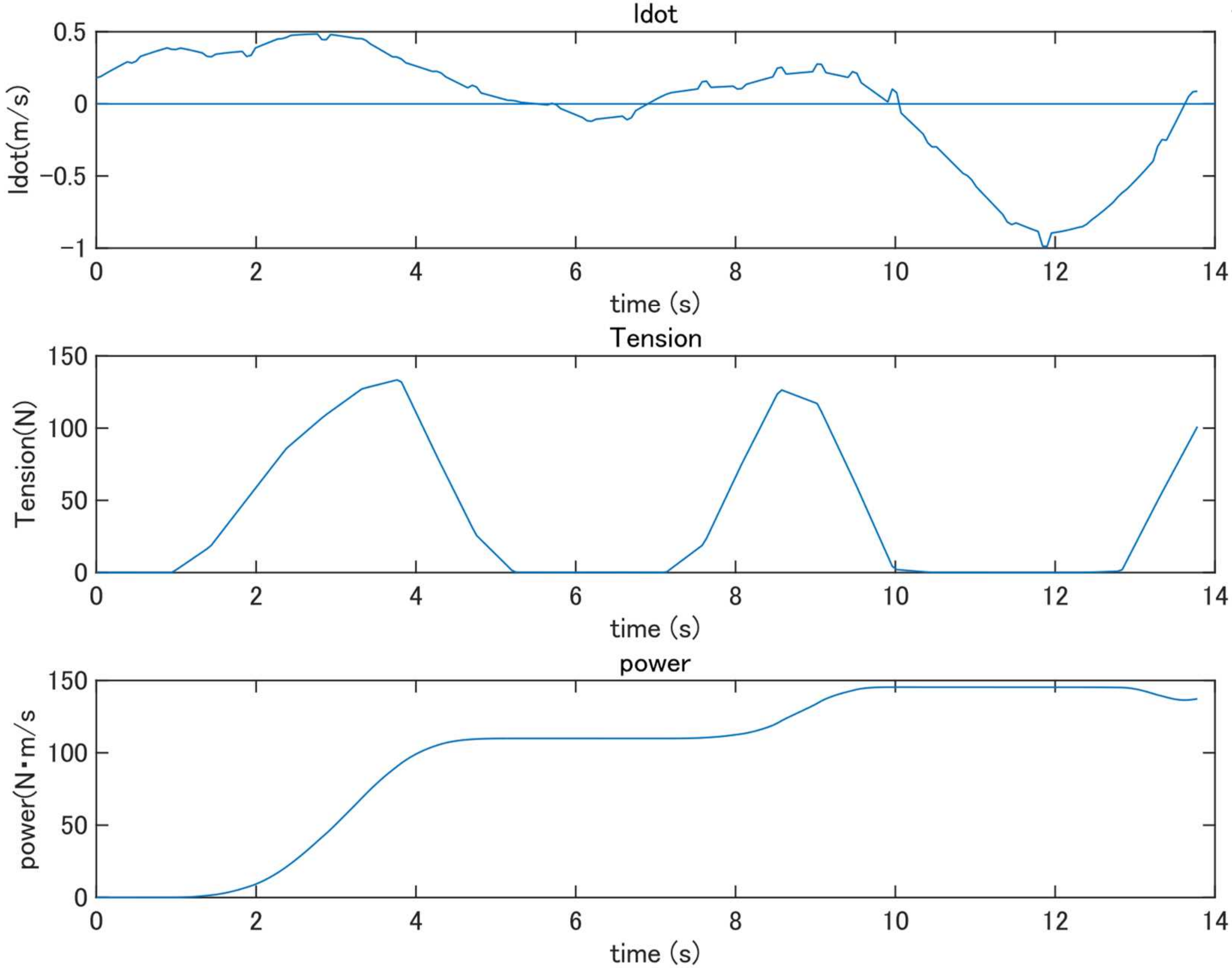
Performance index With turbine

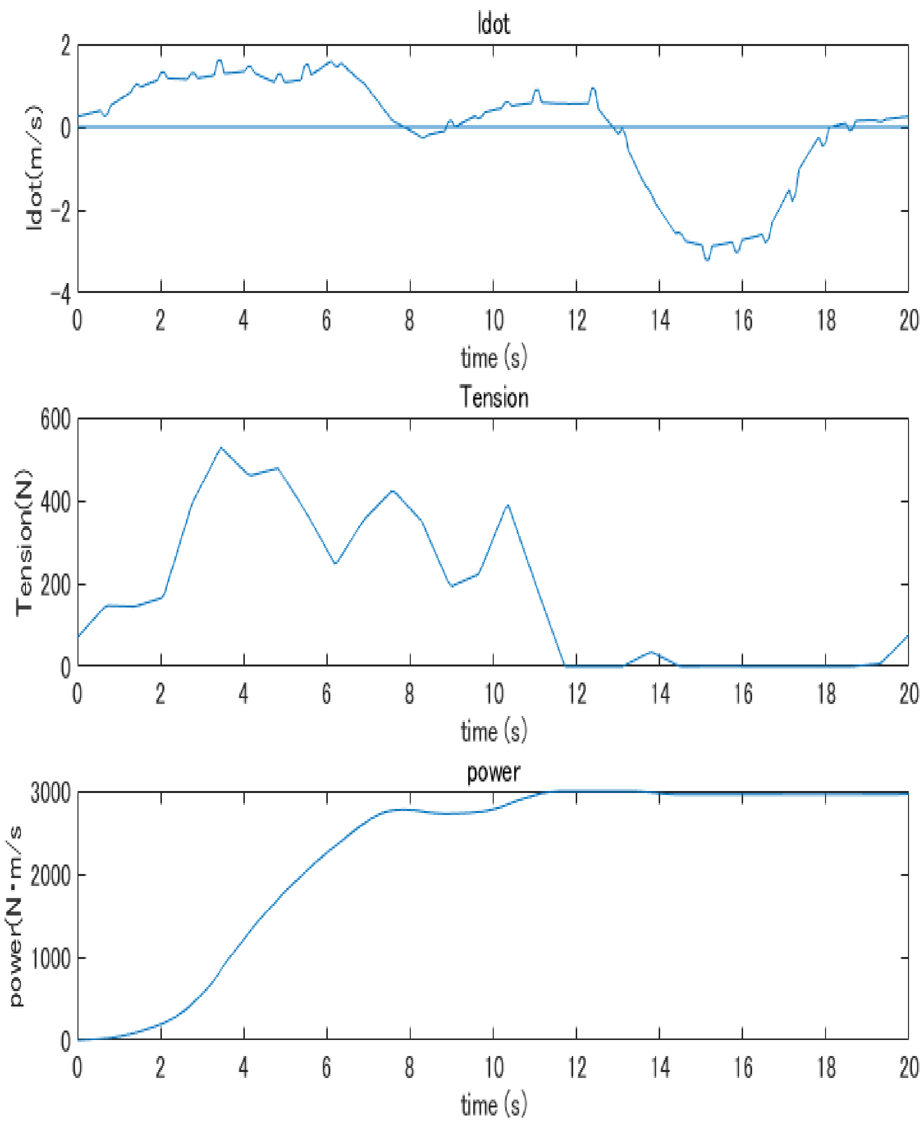
$$J = \int_{t_0}^{t_f} T \dot{\ell} dt$$



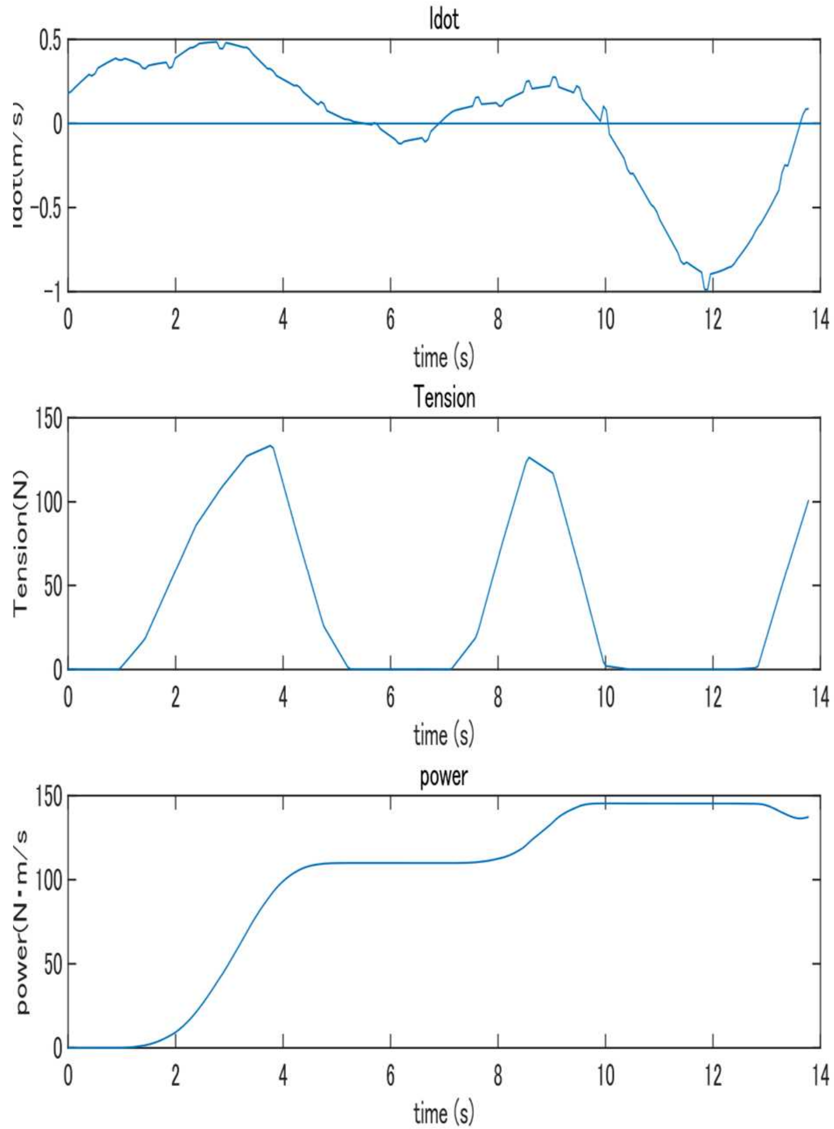
Performance index　Without turbine

$$J = \int_{t_0}^{t_f} T\dot{\ell}\,dt$$





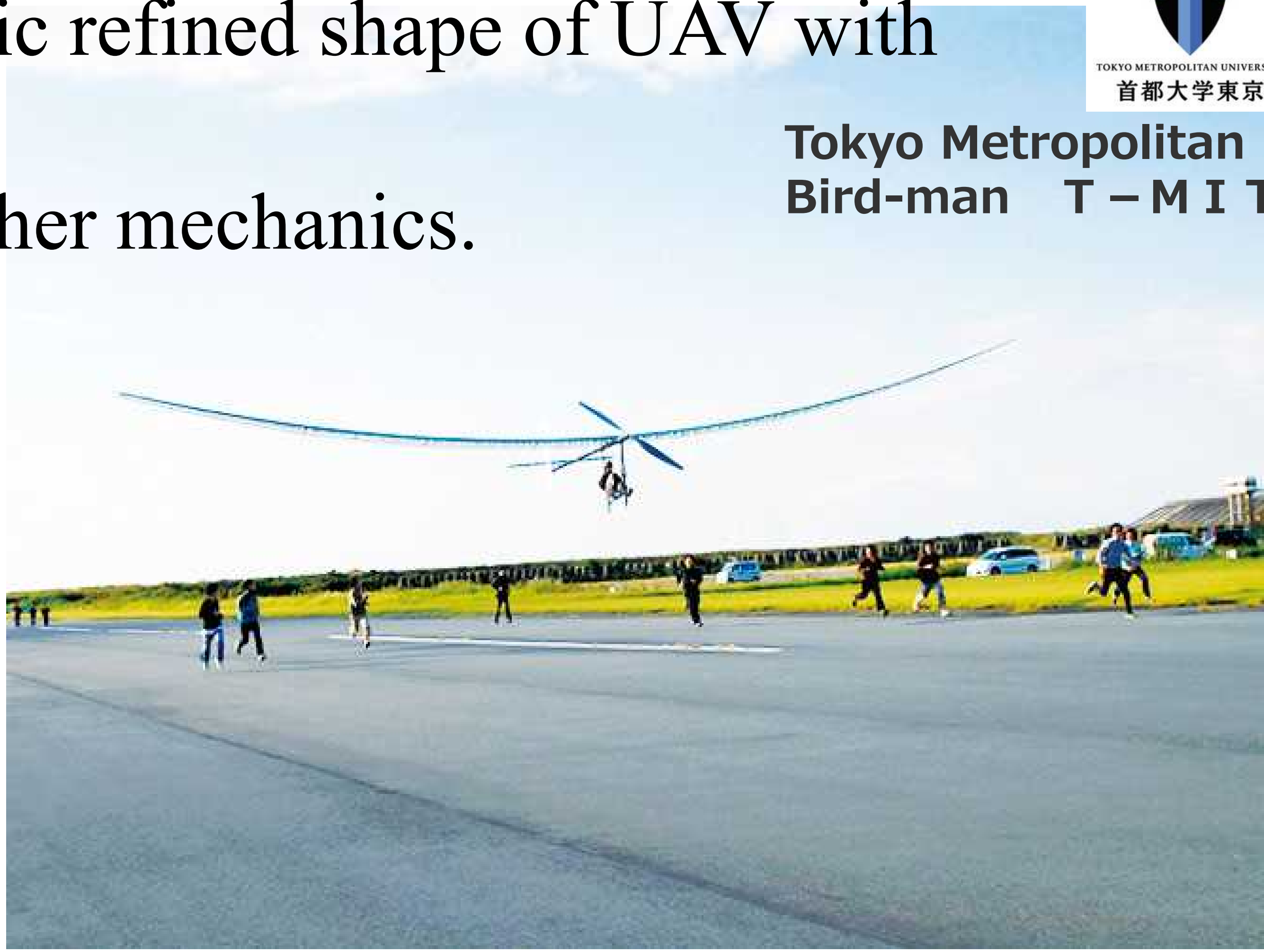
$Cd = 0.0013, CL / Cd = 14$



$Cd = 0.0013 * 4, CL / Cd = 14 / 4 = 3.5$

Further study in long-load to kW ➡ MW class:

- Sophisticated models (Including other effects: Tether drag, etc.)
- Aerodynamic refined shape of UAV with windmills.
- Simplify tether mechanics.



Wind energy on the top of sclaper

Fujii Laboratory

Dynamics and Control of Space Infrastructures