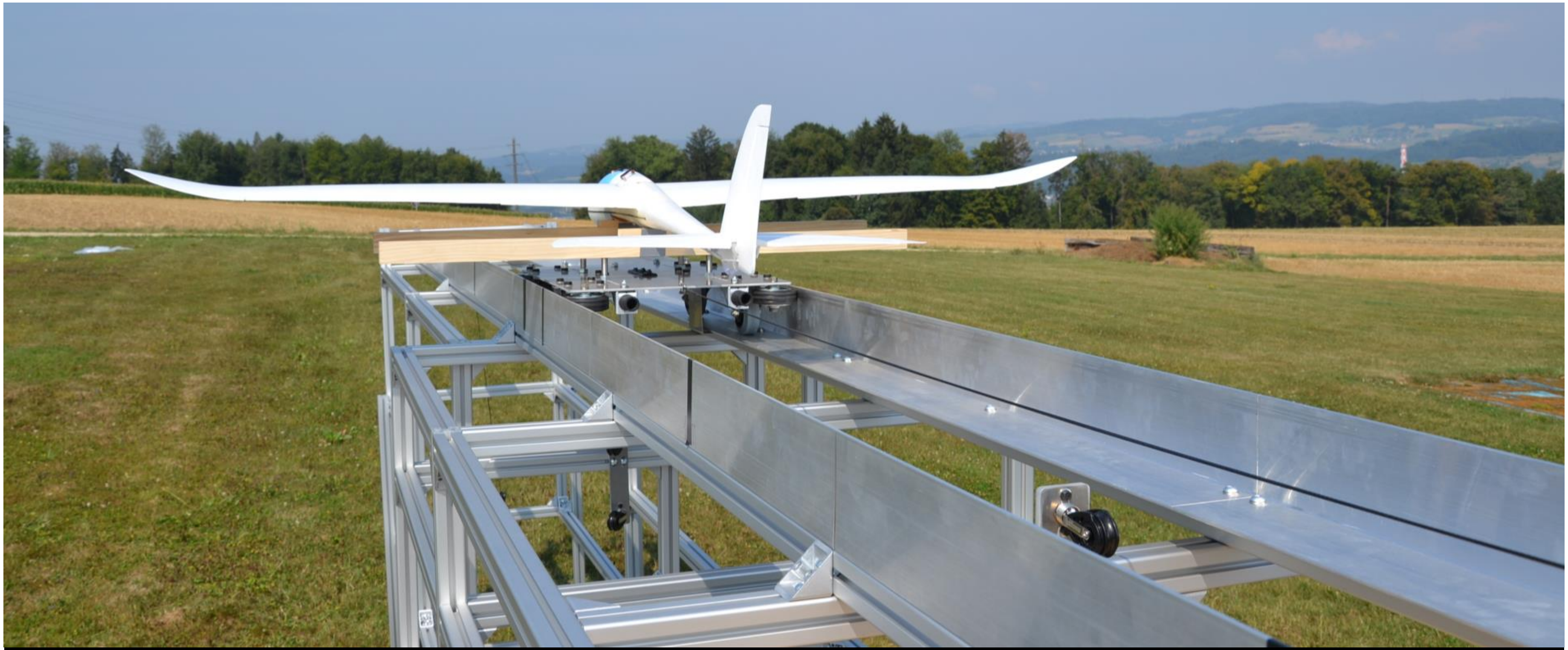


Eric Nguyen Van, Lorenzo Fagiano, Stephan Schnez • ABB Corporate Research • December 8th, 2015

Take-Off and Landing

a Challenge for Lift-Based, Rigid Wing AWE Systems

Power and productivity for a better world™ ABB

Outline

- ABB's Interest in AWE
  - ⇨ assessment of potentially disruptive wind power technology
- Our Choice of an AWE Concept
  - ⇨ rigid-wing aircraft with ground-based electric generation
- Why Investigation of Launch & Landing?
  - ⇨ open challenge for the development of a complete AWE system
- Launch & Landing Demonstrator
  - ⇨ status quo of semi-autonomous launch (incl. videos)
  - ⇨ outlook semi-autonomous landing

ABB's Interest in AWE

- ABB is one of the big suppliers of electrical components for wind power and technology leader in connecting wind farms to the grid (new.abb.com/windpower).
- **CRC monitors and assesses new and potentially disruptive technologies.**
- Our **AWE activity is a technology scouting activity** to diligently assess the potential of AWE:
  - «back-of-the-envelope» estimates
  - numerical simulations
  - (small) experimental setup to investigate key challenges (e.g. launch & landing)
- **Desirable:** Good understanding
  - **whether AWE can live up to ist promise,**
  - **where ABB could contribute in the value chain.**
- It is a small CRC-activity with 0.6 MY of permanent employees.

Our Choice of an AWE Concept
Rigid-Wing Aircraft with Ground-Based Generation

	Rigid-Wing Aircraft (vs. soft kite)	Ground-Based Electric Generation (vs. on-board generation)
advantages	superior aerodynamic performance	**lighter (both aircraft and tether)**
	shorter & more efficient reel-in phase	**(probably) lower capex**
	decades of experience from the development of conventional aircrafts	more potential for ABB with current product portfolio
	better controllability	(probably) more reliable
disad-vantages	higher mass	less uniform power production («yoyo»)
	launch & landing	**launch & landing**
	(probably) higher capex	

However, ABB is technology-open – our assessment may change anytime.

Why Investigation of Launch & Landing (L&L)?

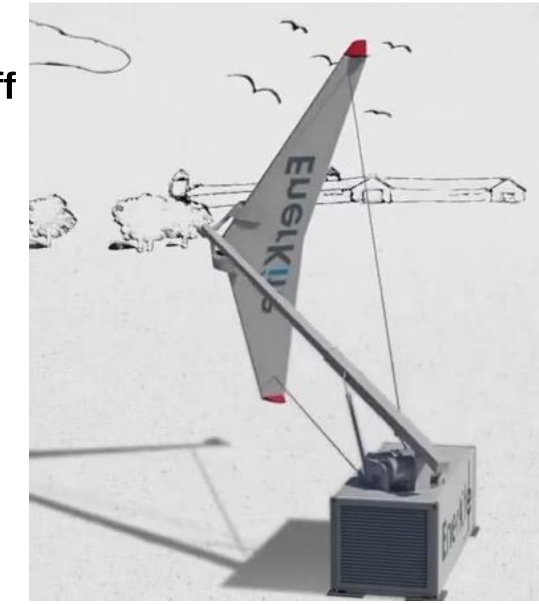
- several companies demonstrated
  - ✓ autonomous flight (full power cycle)
  - ✓ (electric) power generation
  - ✓ grid connection

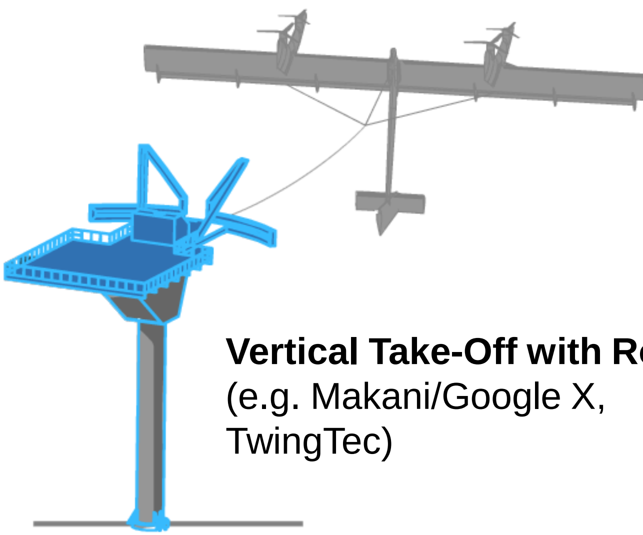
- still to demonstrate
  - ✘ autonomous launch & landing
  - ✘ full system operation:
    - ✘ reliable operation for long time incl. launches & landings (weeks to months)
    - ✘ determination of capacity factors etc. for benchmarking with conventional wind/other sources of electric power

Launching Methods

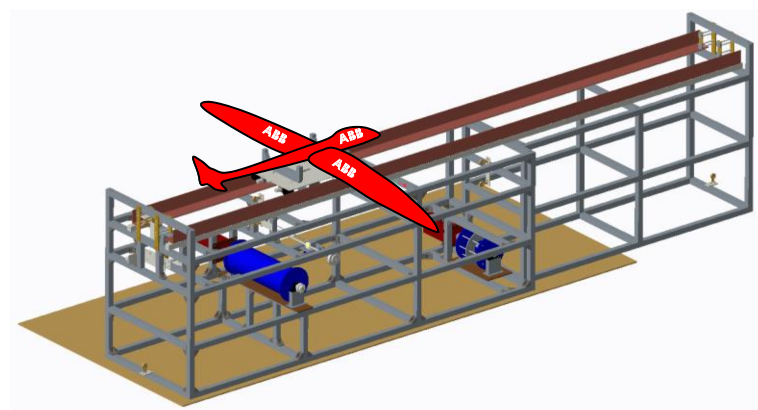
Kite Launch
(e.g. SkySails)

Rotational Take-Off
(e.g. EnerKite)





Vertical Take-Off with Rotors
(e.g. Makani/Google X, TwingTec)



Winch Acceleration to Take-Off Speed plus On-Board Propeller for Climb Flight
(e.g. Ampyx Power)

Performance Criteria for Launch & Landing

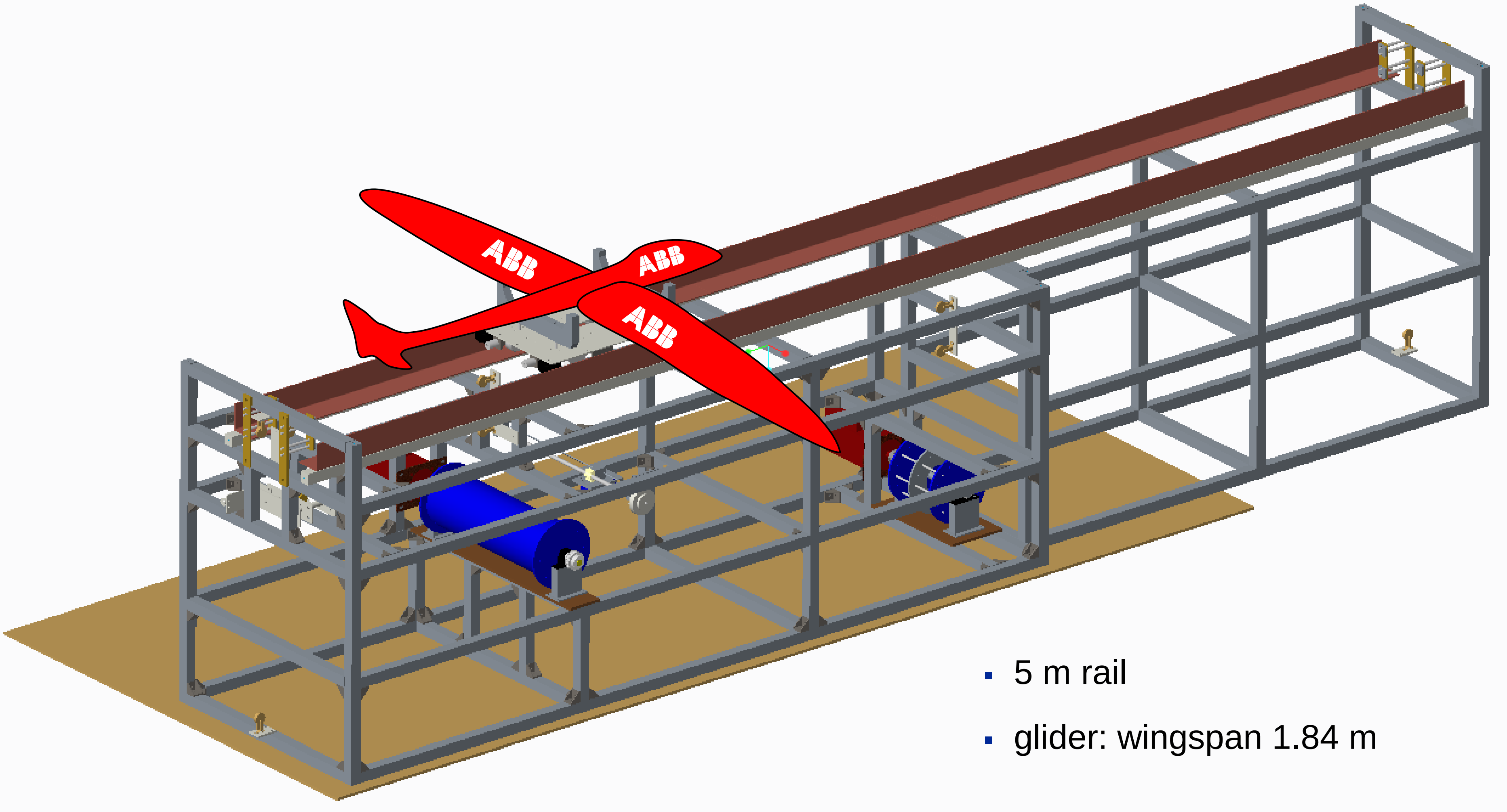
Qualitatively:

1. L&L capability should not have a significant influence on the overall AWE system design (in particular the aircraft).
2. Power production capability should define system design and costs.
3. L&L capability should be «scale-invariant» or scale sub-linearly with system size.
4. capable of L&L under most wind conditions (incl. no wind)
5. L&L capability should only require a small footprint.

Based on our qualitative and quantitative criteria, we selected a linear launch method with little on-board propellers.

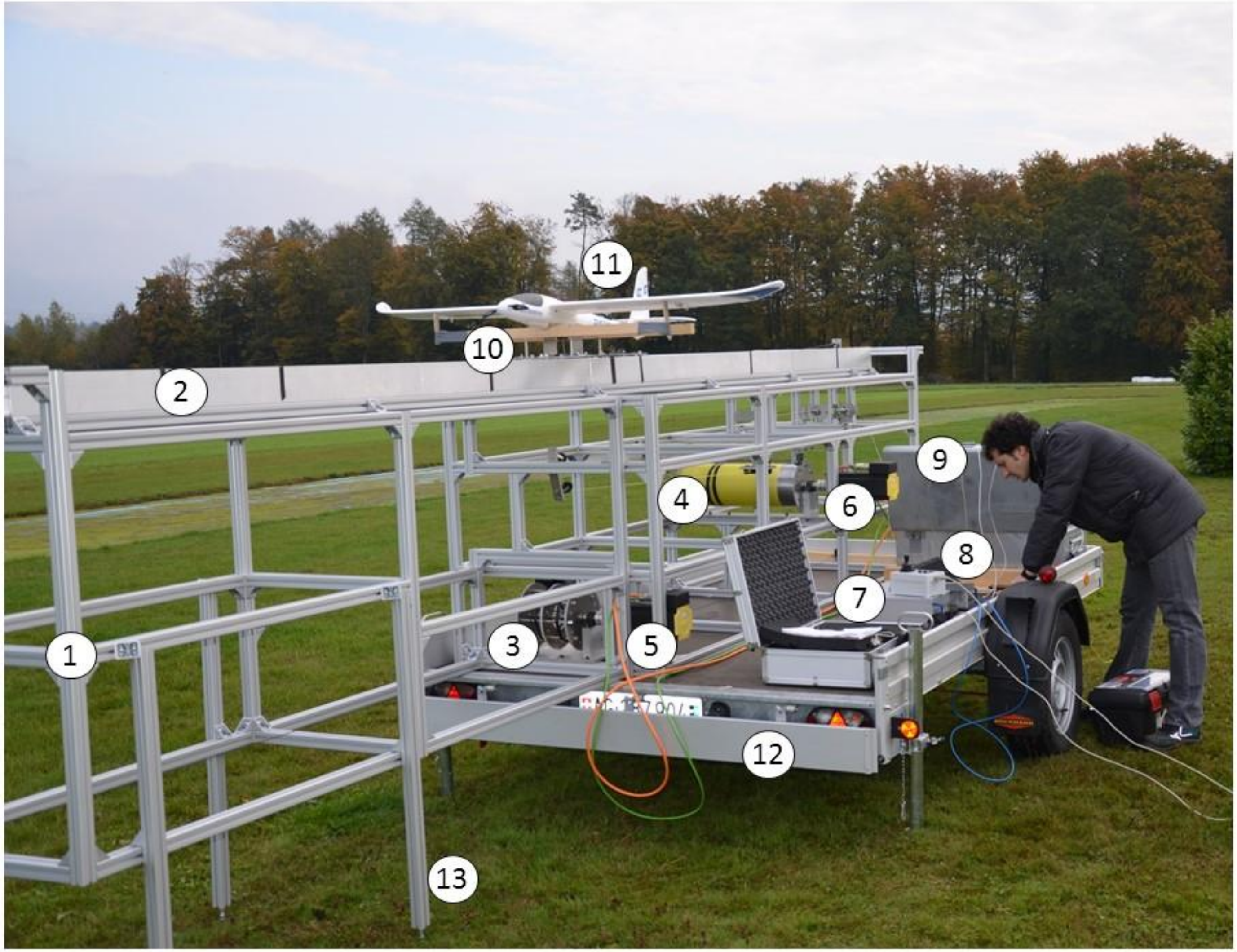
see: Fagiano & Schnez, *On the Take-Off of Airborne Wind Energy Systems Based on Rigid Wings*, submitted (2015), arXiv:1510.06701

Launch & Landing System



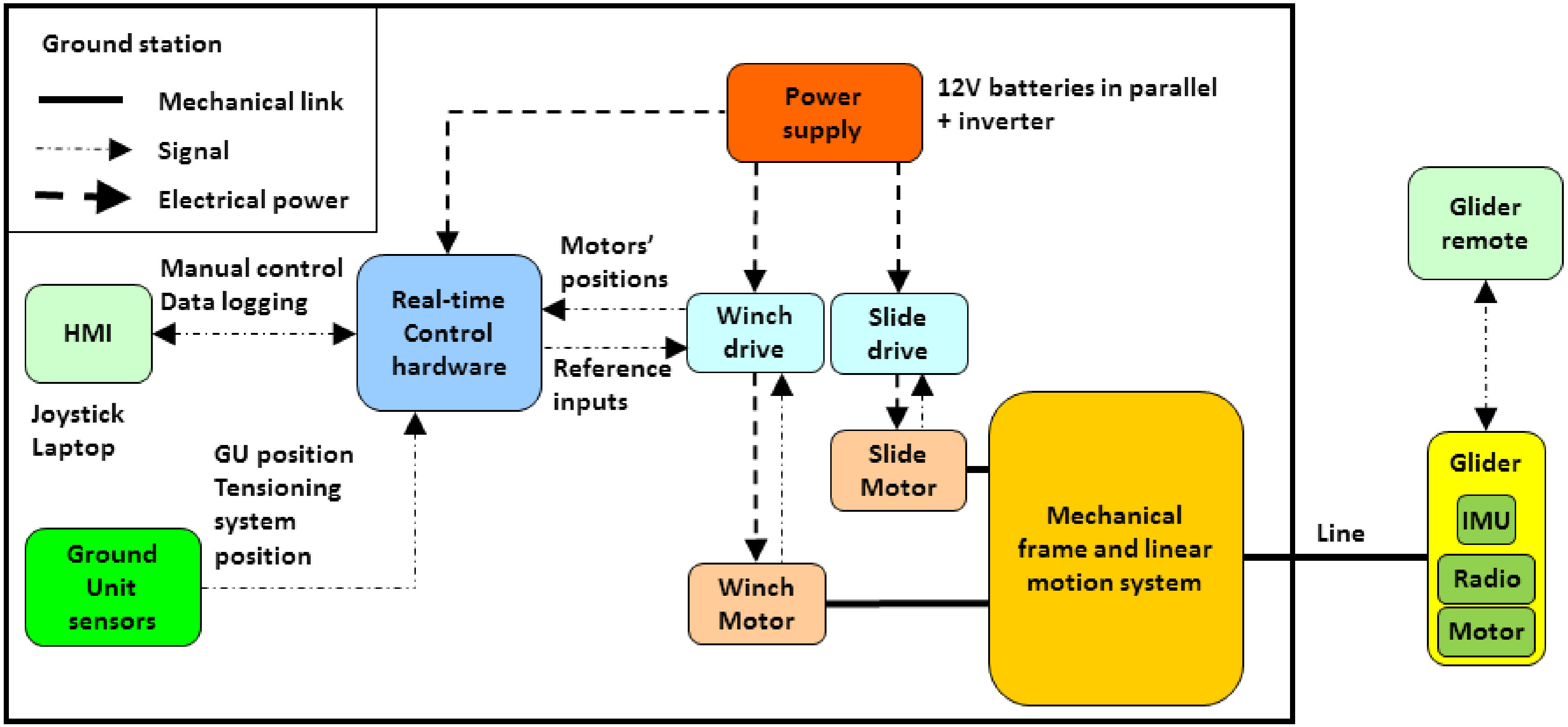
- 5 m rail
- glider: wingspan 1.84 m

Launch & Landing System



1. frame
2. rails
3. slide drum
4. winch drum
5. slide motor
6. winch motor
7. RTM
8. HMI
9. box with batteries, drives etc.
10. slide
11. glider
12. trailer
13. feet for frame

Launch & Landing System

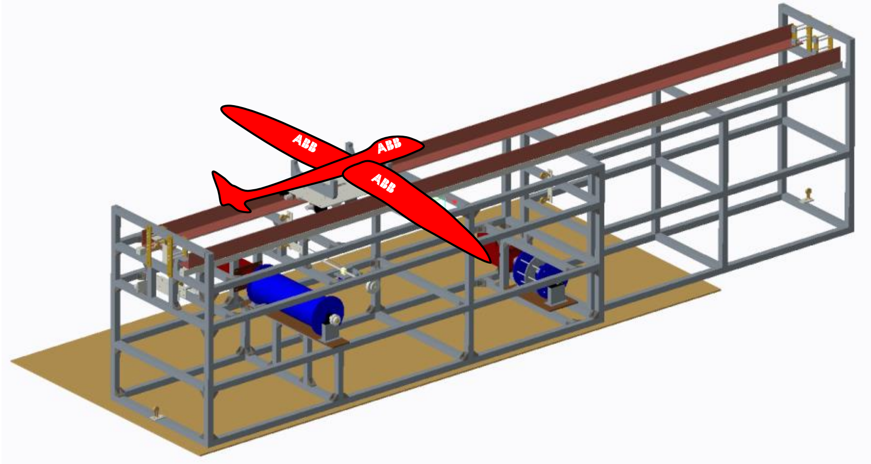


Launching
Winch Acceleration Plus On-Board Propellers

two phases:

1. **accelerate plane to take-off speed with winch** on slide & rail
   $\frac{P_{acceleration}}{P_{gen}} \sim 10 - 11\%$
2. **propulsion during climb with on-board propellers** at constant speed
   $\frac{P_{propellers}}{P_{gen}} \sim 3 - 4\%$ (two propellers)

- ✘ some **additional on-board and on-ground components**
- ✘ climb flight covers rather big area
- ✓ on-board propellers can fulfill **additional functionalites**
- ✓ **length of rail independent of system size**
- ✓ **winch for acceleration available** anyway
- ✓ **orientation with wind direction** possible



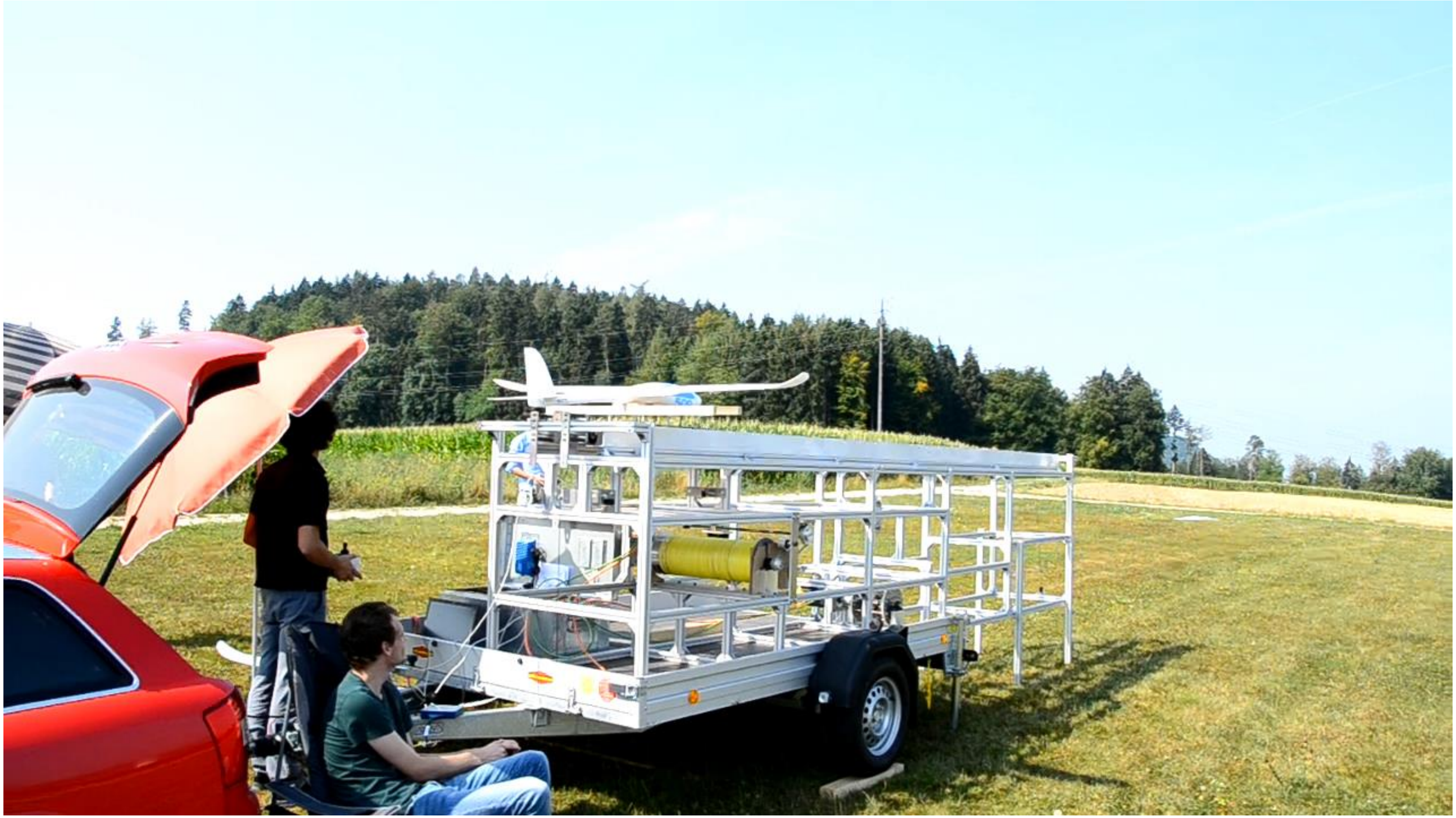
see: Fagiano & Schnez, *On the Take-Off of Airborne Wind Energy Systems Based on Rigid Wings*, submitted (2015), arXiv:1510.06701

Launching Procedure

- automation of ground station: power winch and slide winch
- control of glider:
  1. human-piloted initially
  2. then: automation planned (depending on time and necessity)
- potentiometer from line-tensioning system is only input for controller of the power winch
- two control phases:
  1. acceleration sequence, glider on slide
  2. climb sequence, slide slows down/at standstill

Videos of Launches

Videos of Launches



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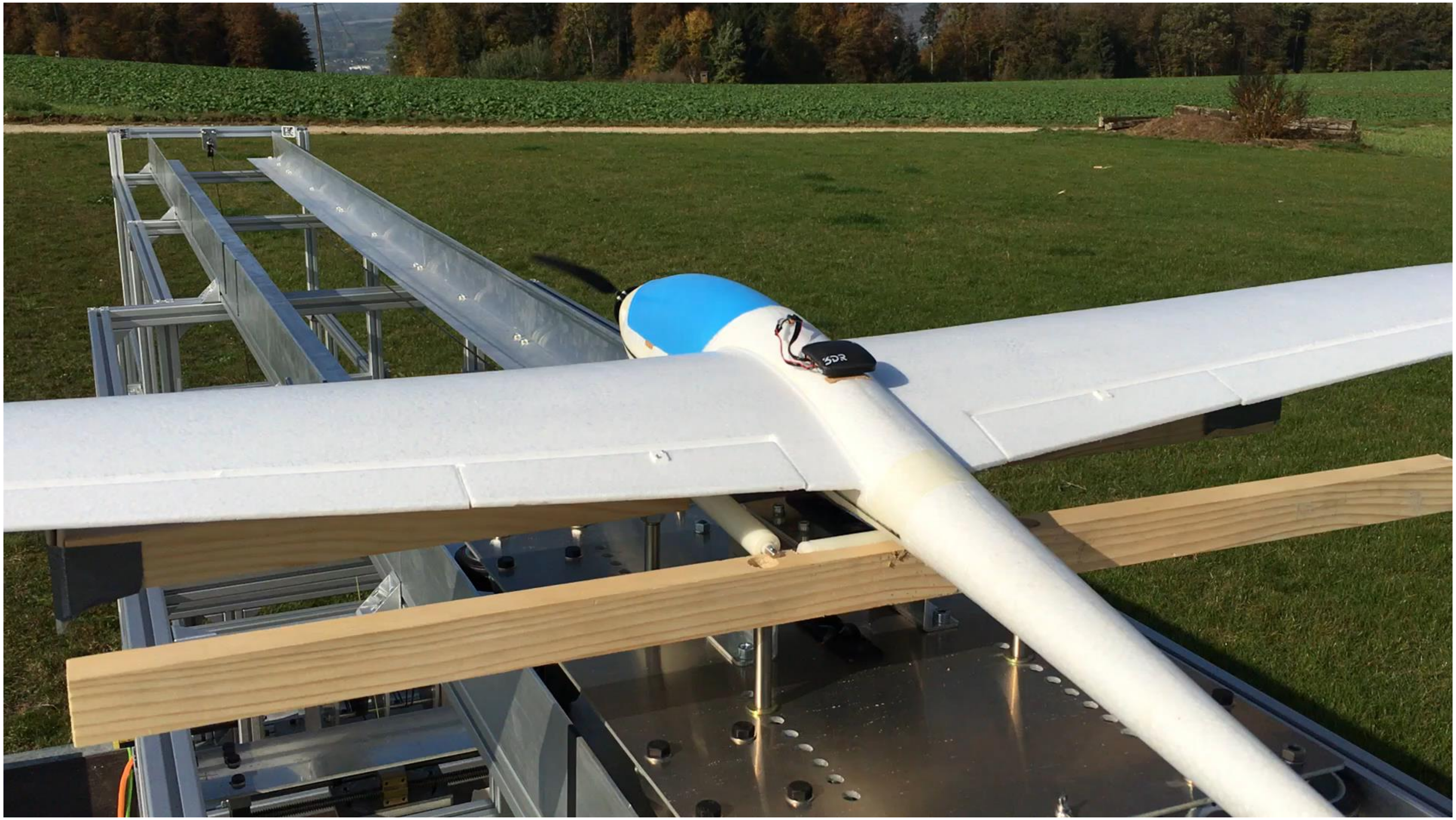

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Videos of Launches

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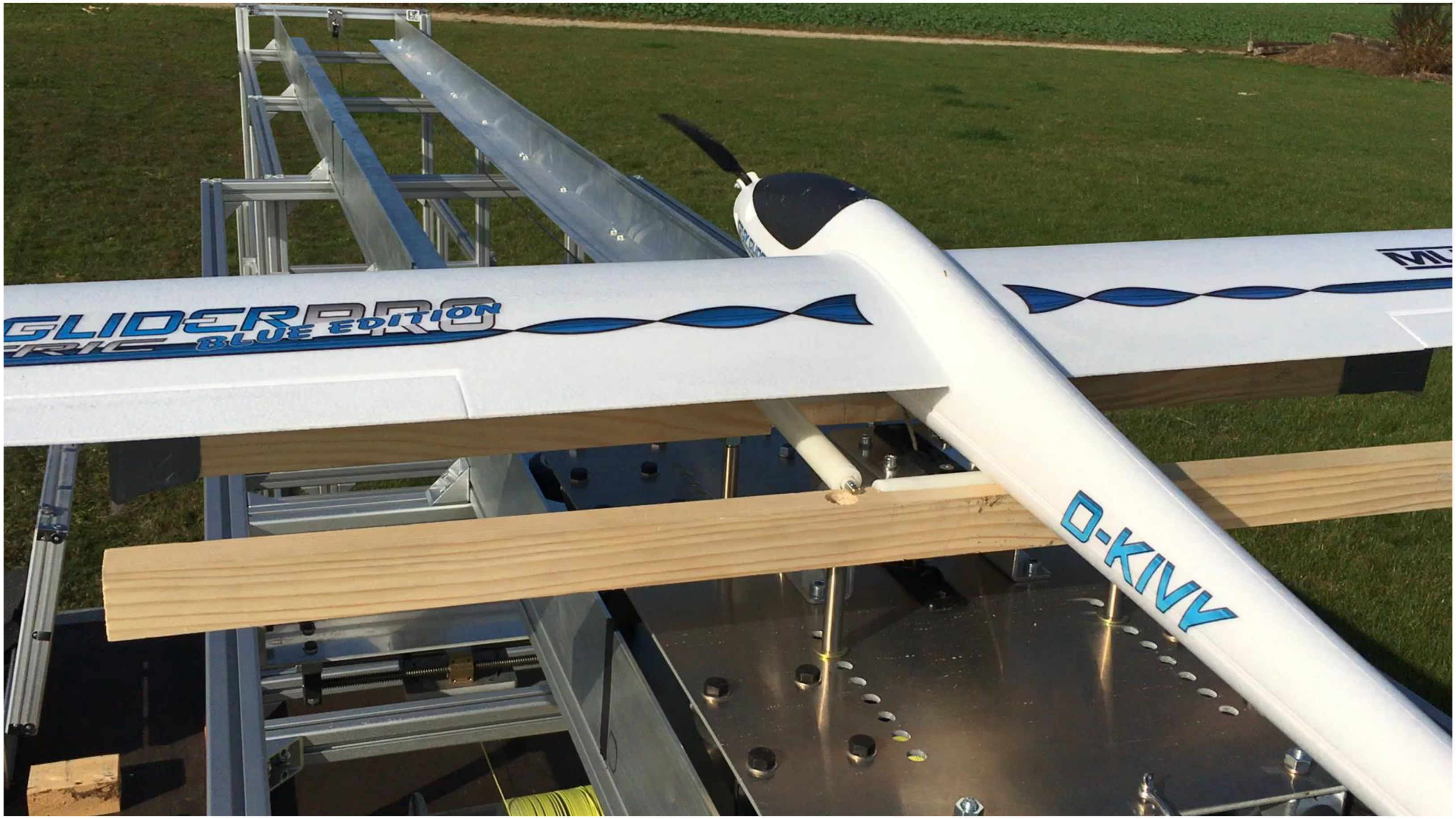

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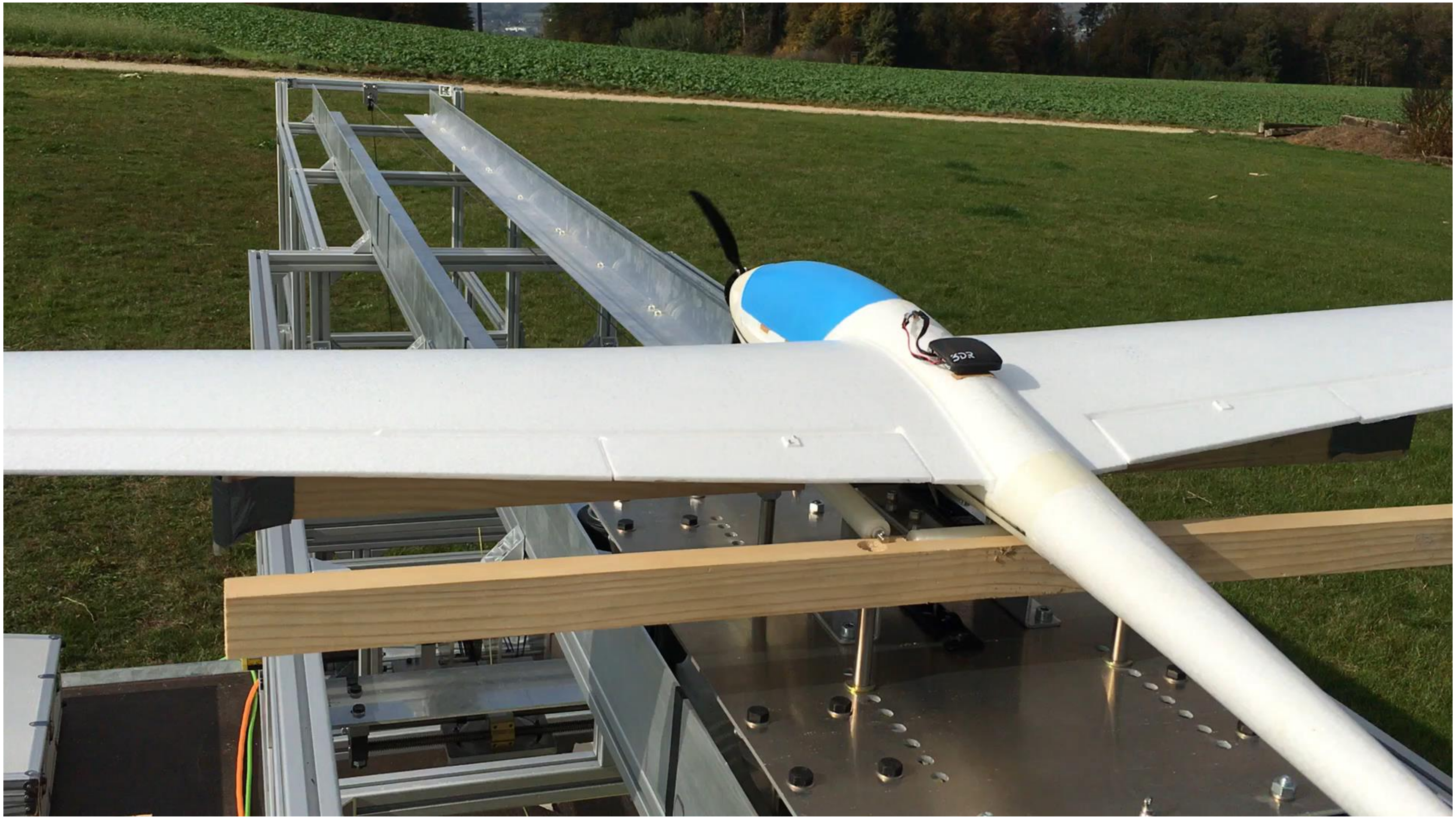
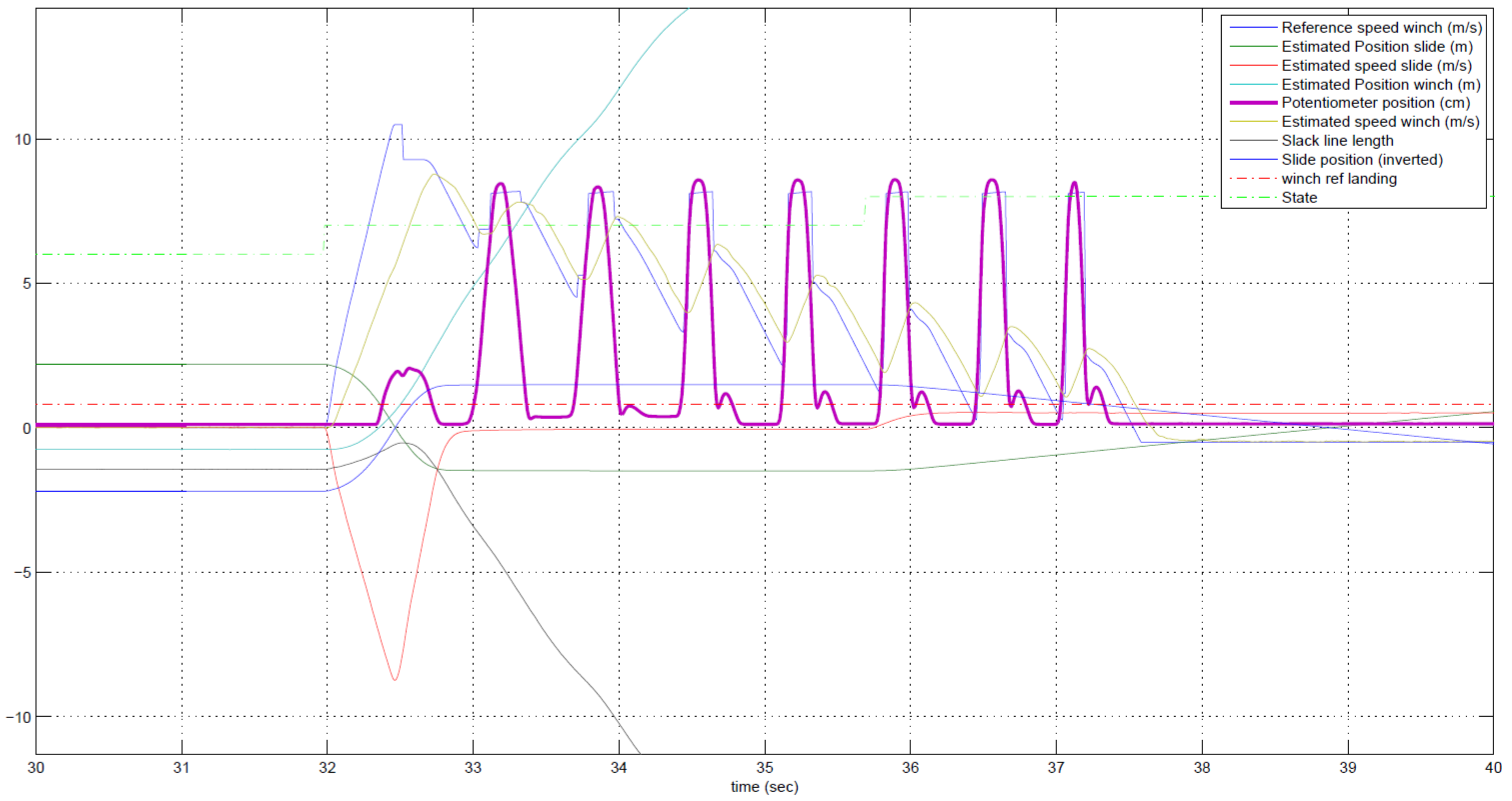
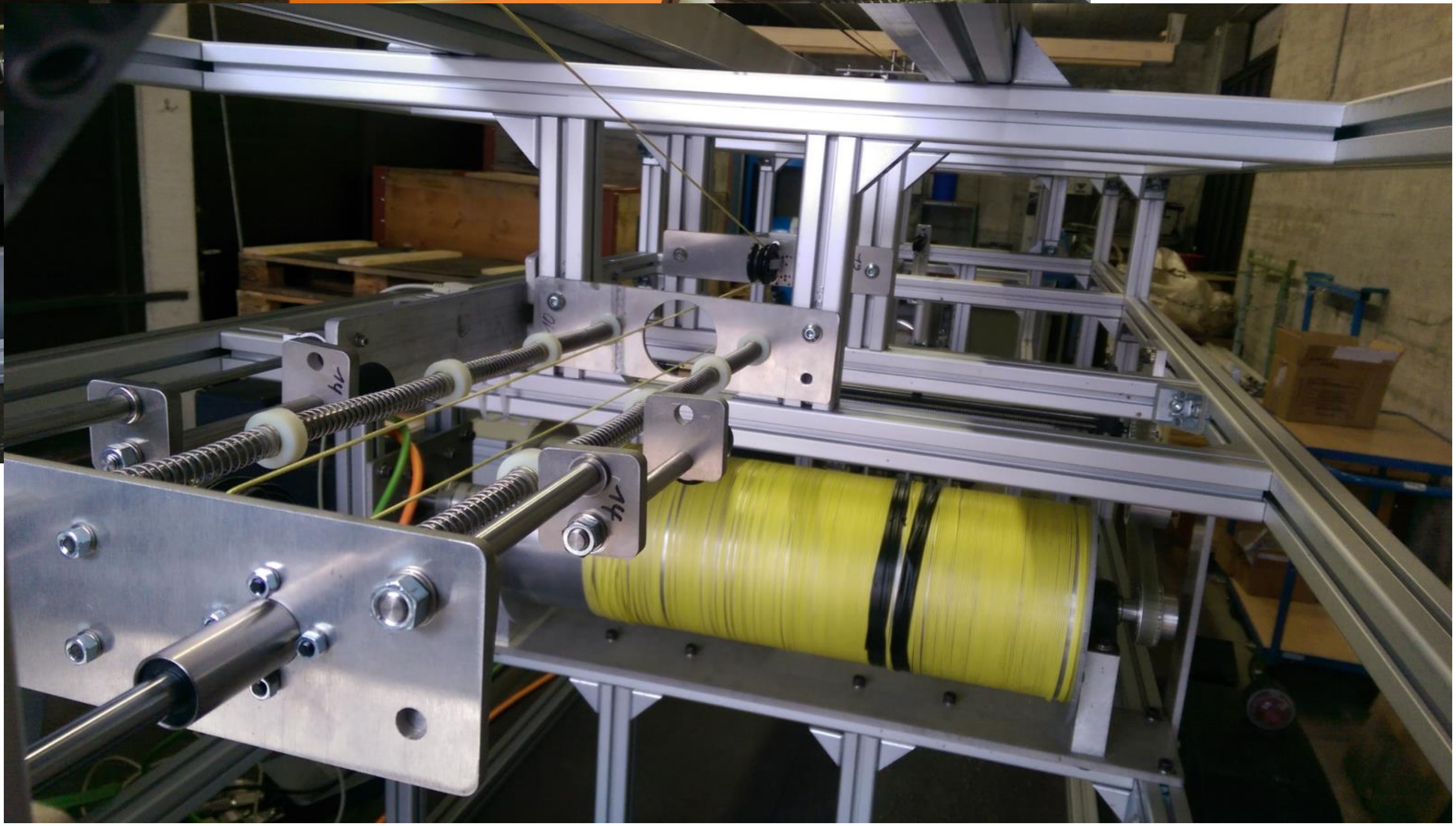


Videos of Launches

Oscillating Line-Tensioning System



Line-Tensioning System



Challenges for the Launch

- difficult control task:
  - inertia of the winch drum big compared to the inertia to the glider
  - winch motor was designed for launch; winch drum would be capable of handling power cycles & heavier gliders
  - line tension:
    - «almost» sagging line to exert no/only very little force on glider during climb
    - avoid line entangling
    - some force required to have input for feedback
  - ⇨ **bad design!**

- solutions:
  - increase spring deflection
  - decrease friction (as few pulleys as possible etc.)
  - re-design drum, if necessary

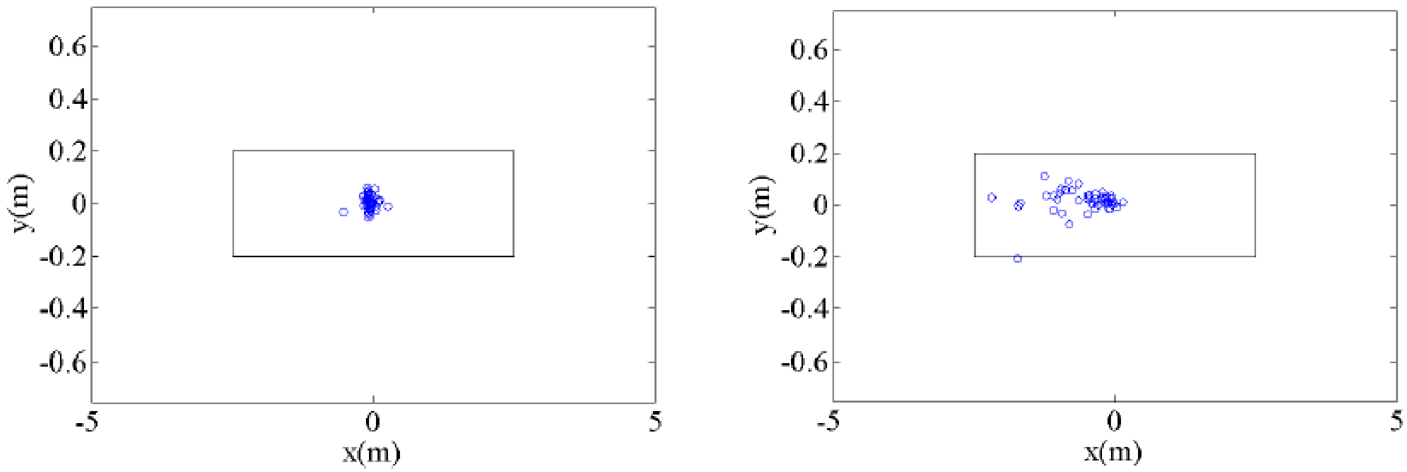
Outlook: Landing Procedure

- «conventional» landing with tether
  - small approach angle
  - small force on tether → guiding the glider
  - accelerate slide so that relative speed is zero
  - touch-down on slide and braking of slide

- discussion of alternative landing schemes
  - deep-stall landing?
  - others

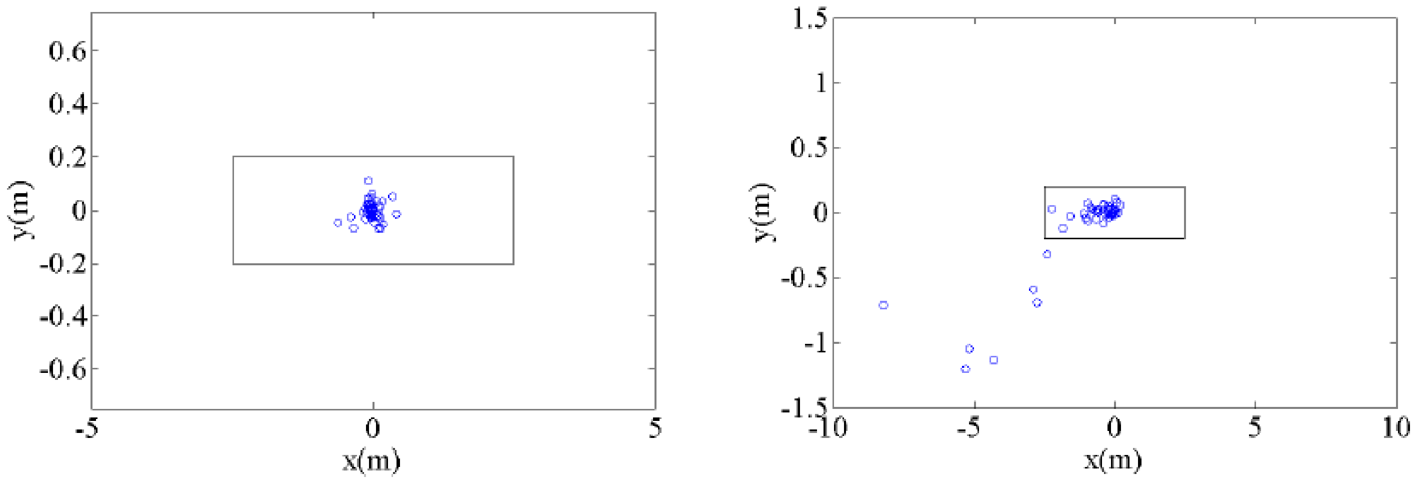
Outlook: Landing Precision

specific weight 3.8 kg/m²　　　specific weight 8 kg/m²



wind speed 4 m/s

(c)



wind speed 6 m/s

see: Fagiano, Nguyen Van & Schnez, *Linear Take-Off and Landing of a Rigid Aircraft for Airborne Wind Energy*, submitted (2015)

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Summary

- ABB's interest in AWE:
  - potentially disruptive wind power technology
  - Where can ABB contribute in the value chain?
- our favorite concept: rigid wing with ground-based power conversion
- autonomous L&L as one of the main remaining challenges
- winch acceleration to take-off speed and on-board propellers for propulsion during climb
- landing by touch-down on slide and subsequent slow down

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L&L Criteria

$$\overline{P}_{g,i} \simeq \eta_{P_g,i}\, P_m^*$$
$$\overline{P}_{ob,i} \simeq \eta_{P_{ob},i}\, P_m^*$$

$$\Delta m_i \simeq \eta_{m,i}\, m$$

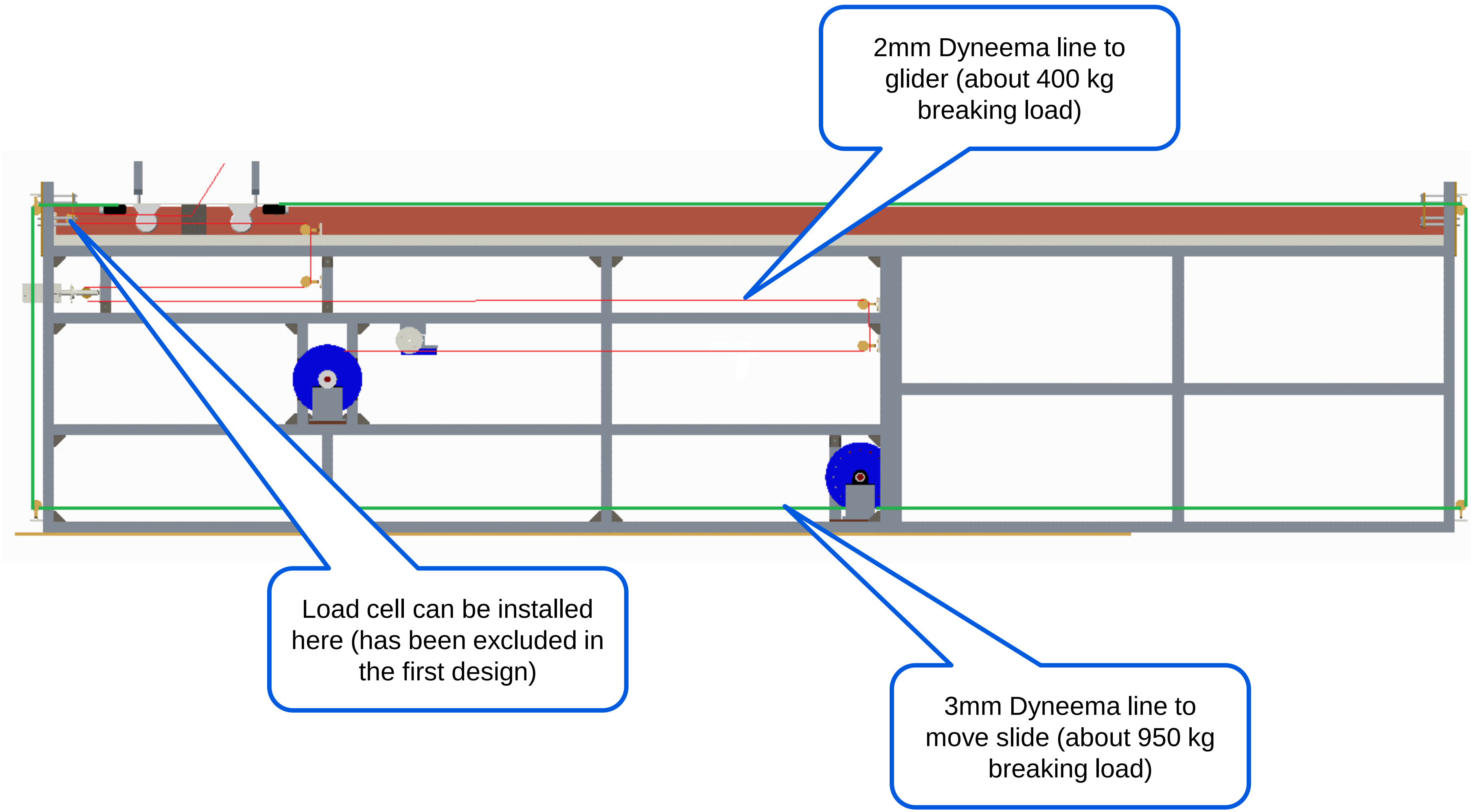
$$A_{g,i} \simeq \underline{A}_{g,i} + \eta_{A_g,i}\, A,$$

	C1: power		**C2**: mass	**C3**: area	
Concept	$\eta_{P_g,i}$ (%)	$\eta_{P_{ob},i}$ (%)	$\eta_{m,i}$ (%)	$\underline{A}_{g,i}$	$\eta_{A_g,i}$ (%)
Vertical	0	19	21	0	$\frac{\pi\lambda}{4}$
Rotational	4	0	0	$\frac{\pi R^2}{4}$	0
Linear	11	3	5	$\frac{\pi L^2}{4}$	$\frac{\pi\lambda}{4}$

Rotational launch looks attractive; however there is a minimum value for *R* which is rather big, small velocities at ground level are required, and there is the probleme with varying relative wind speed if there is some wind.

⇨ The linear launch is the most attractive one.

Launch & Landing System
Line Arrangement



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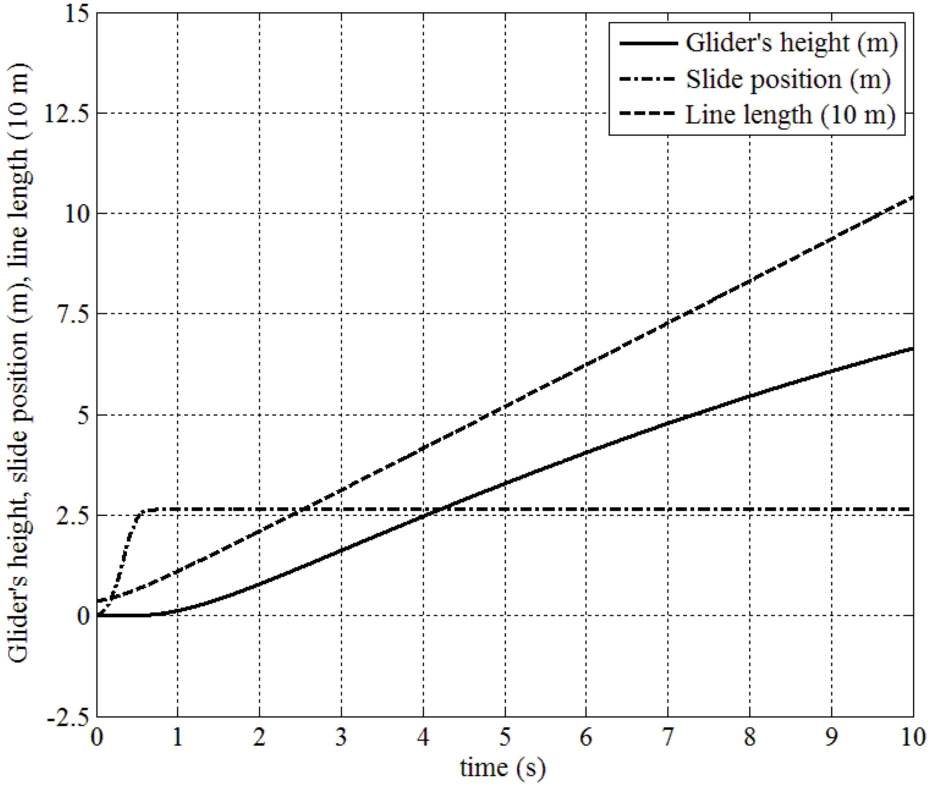
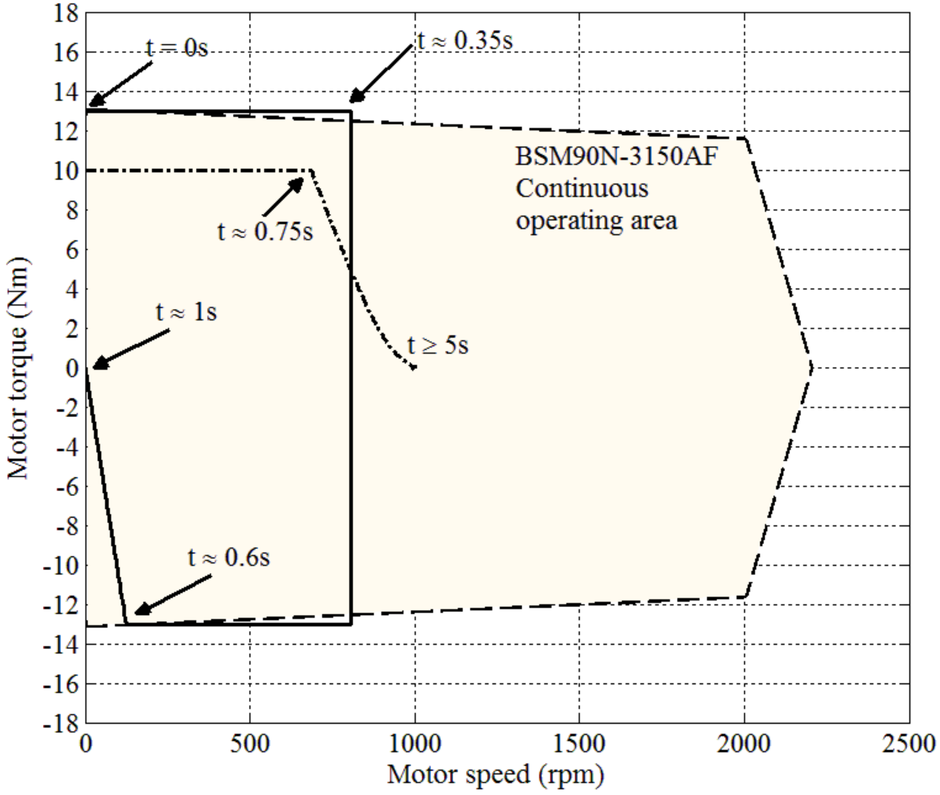
Launch & Landing System
Simulated Behavior





Glider and Flight Communication/Control

Criteria	YoYo Glider
Wing Span (m)	1.84
Weight (g)	900
Motorization	180 W
Body Volume	+
Material	foam
Body stiffness	+
Position of Stabilizer	down
Position of motor	front
Flaps	yes

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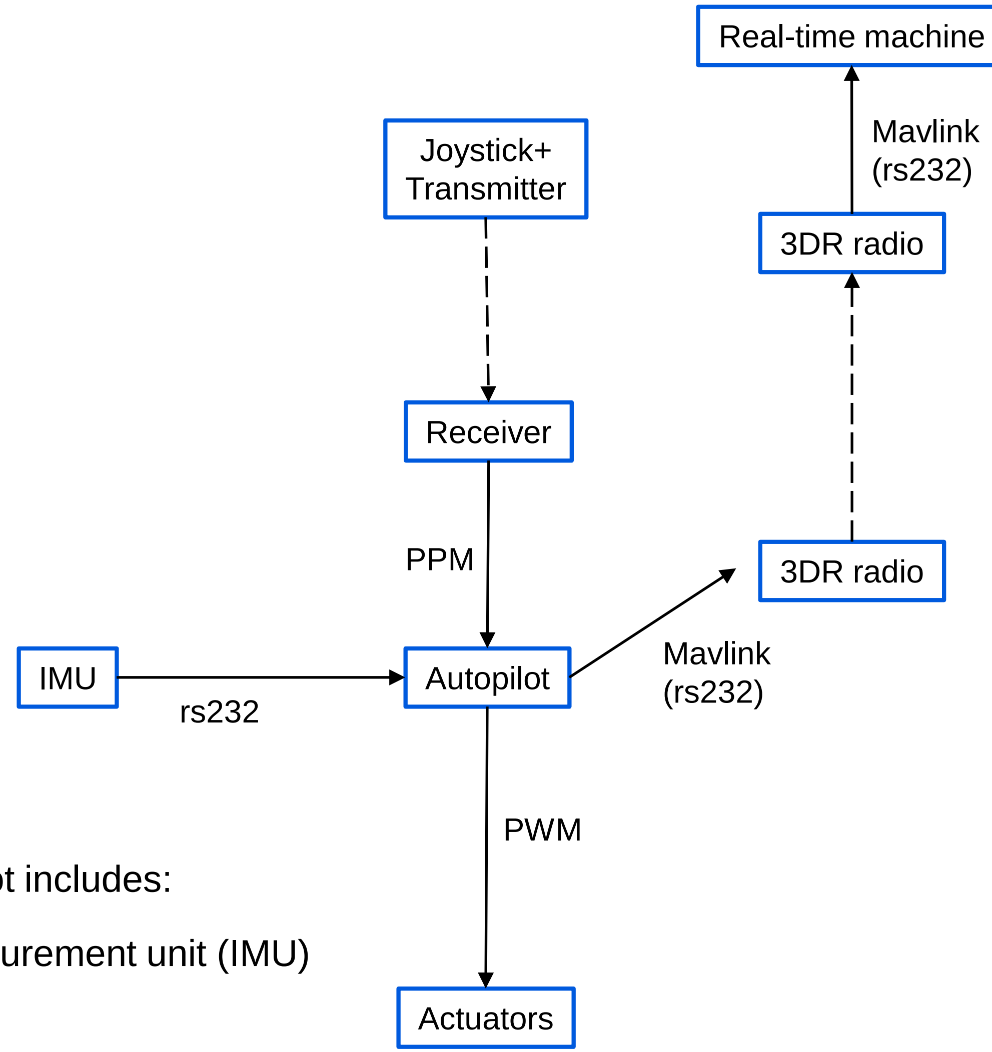
Glider and Flight Communication/Control



pixhawk autopilot includes:

- inertial measurement unit (IMU)
- GPS
- Pitot tube