Research and Development of a Multi-copter for Autonomous Inspection of Headrace Tunnels of Hydraulic Power Stations

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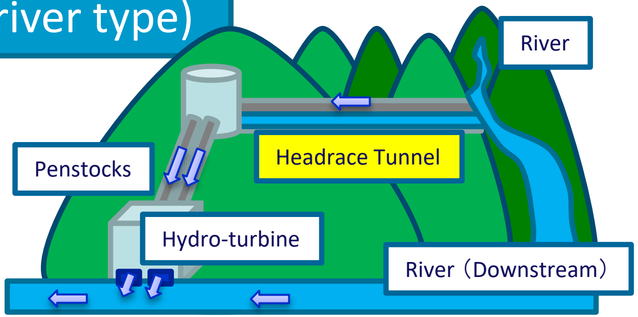
Background: Maintenance of Hydro Power Stations

Large-scale earthquakes
e. g. 2016 Kumamoto earthquakes：(Magnitude 6.2 -> 7.3 -> 7.1->… 400 times, in a week)

Flood Disasters
Typhoons, Torrential rains -> landslides, floods, etc.

Typical hydraulic power station (run-of-river type)



➡ It is necessary to ascertain damages of facilities.

Inspection by workers is dangerous.
Unmanned inspection systems should be developed.

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Autonomous Drone for Disaster Response

Why drones in headrace tunnels ?

1) Water or sediment remains on the floor.
2) There are large step structures or steep slopes.
3) Distances can range to several kilometers.

Technical issues

1) Many tunnels have smaller cross-sections than traffic tunnels.
2) GPS is not available and radio control from the outside is difficult.
3) No lighting facilities.
4) Hard environmental conditions, including water leakage from ceilings.

Today's topics

- Development of a prototype of TUNNEL DRONE system
- Investigation of aerodynamic characteristics

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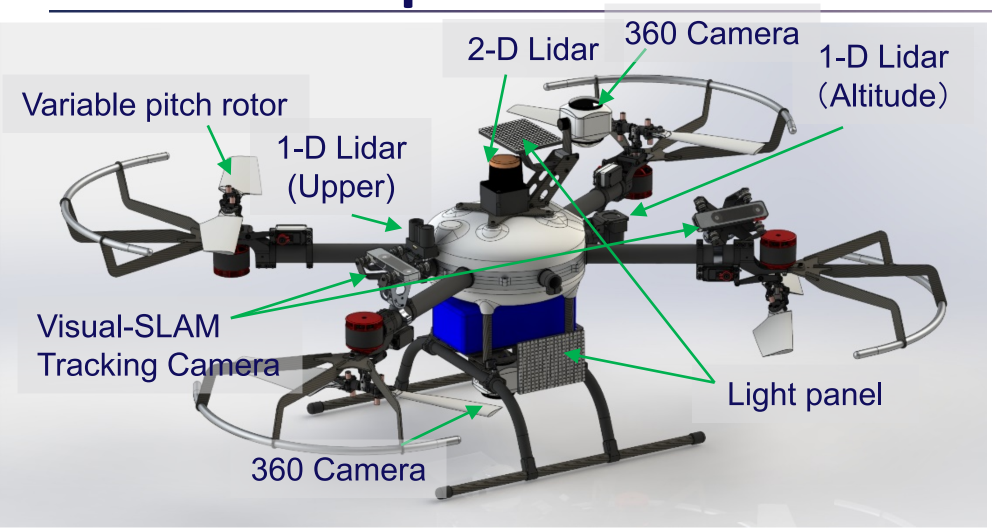
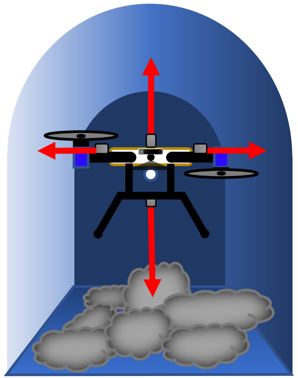
DEVELOPMENT OF A PROTOTYPE OF TUNNEL DRONE SYSTEM

Specifications of the Aircraft





Fully autonomous flight system

- ✓ High maneuverability
- ✓ Robust sensing and navigation system

Rotor	4 Units/15 inched/2 blades：5400r.p.m. +Variable pitch control
Battery	Li-Po 6S 20000mAh （Flight duration 12 minutes）
Dimensions	1074(L) x 806(W) x 320(H) mm
Waterproof / dustproof	IP55
Veridical positioning	Upper/lower wall distance control or Altitude control
Horizontal positioning	Left/right wall distance control

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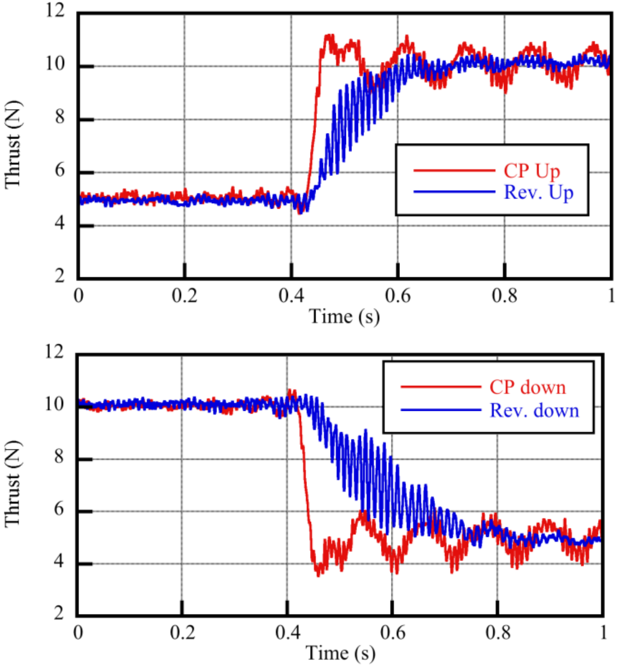
Rotors

Thrust control by variable collective pitch:
Quicker response than rotational speed change

High maneuverability contributes to stabilize the attitude and motion of the aircraft in turbulence in tunnel.



Collective pitch control vs rotational speed control

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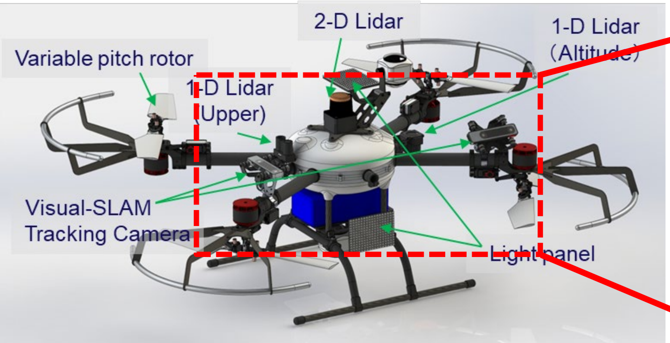
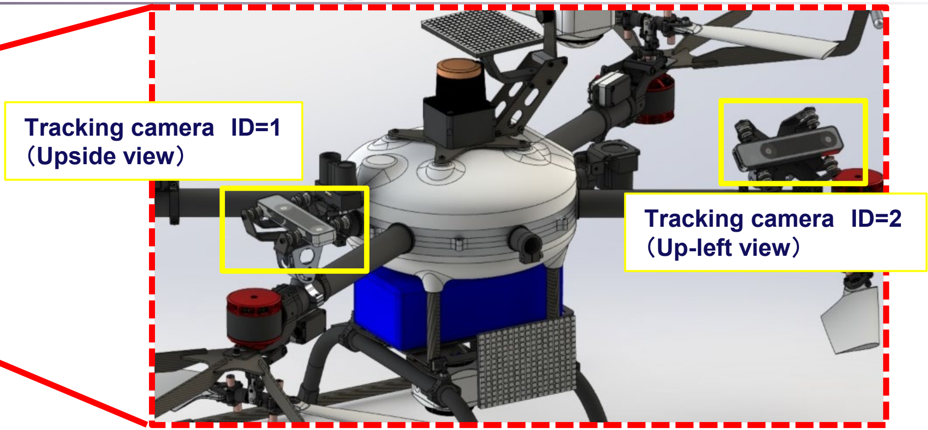
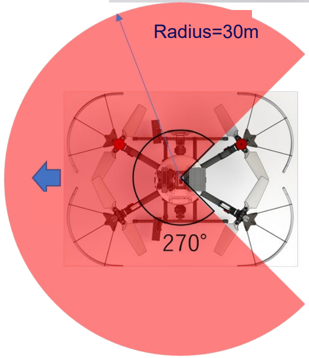
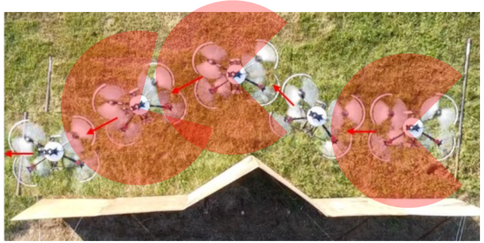
Sensors and Navigation







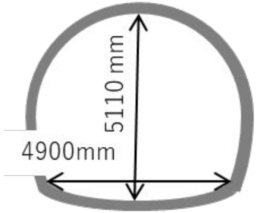


Speed detection using 2 tracking cameras

- ✓ Switching/restarting are possible in case of error
  →Robustness is enhanced by redundant system
- ✓ View in two directions (Upside and up-left directions):
  Autonomous flight is possible even when water remains on the floor
- ✓ Seamless flight through tunnels and open conduit is possible

2-D LiDAR detects obstacles and walls in front and on the side.
Smooth distance control are realized even when the wall surface has discontinuous curve.

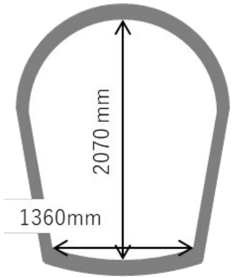
Flight Demonstration (1)

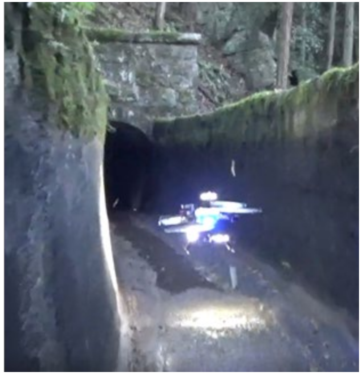


MISSION:
A) Flight in low temperature（-5℃）
B) Flight in fog

- Low temperature→ Condensation occurs on optical sensors
- Fog→ Cause of Visual-SLAM error = Significantly exceeded target point

Flight Demonstration (2)





MISSION:

1. Flight in tunnels with small cross sections
2. Flight in a water conduit with a series of tunnels and open channel

- Small cross sections -> Highly turbulent around the aircraft
- Dirty water droplets from the ceiling in tunnel / Flying leaves in open channel

Variable-pitch-rotors contributed to the flight in turbulence.
Robust optical-system maintained SLAM in various disturbances.

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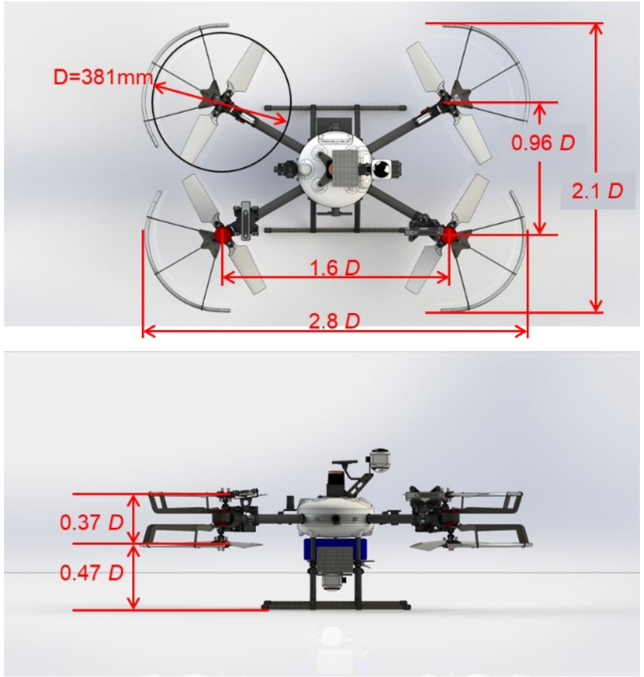
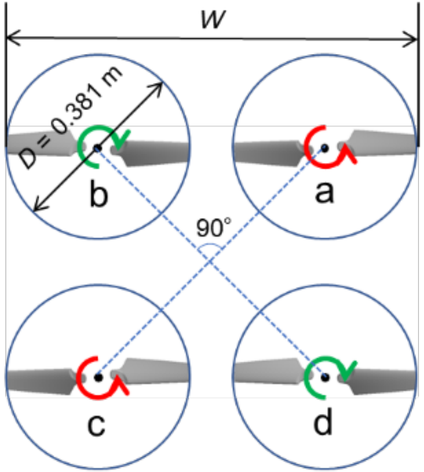
INVESTIGATION OF AERODYNAMIC CHARACTERISTICS

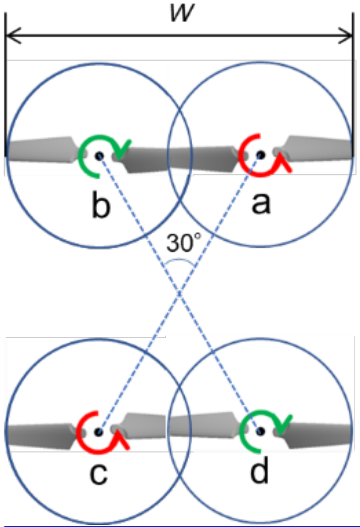
Geometry of the TUNNEL DRONE



D: Rotor diameter (381 mm)



Symmetric configuration



Asymmetric config.
a/d: Upper, b/c: Lower
There is overlap on the left and right propeller rotation planes.
Narrow width is advantage for flight in small tunnel

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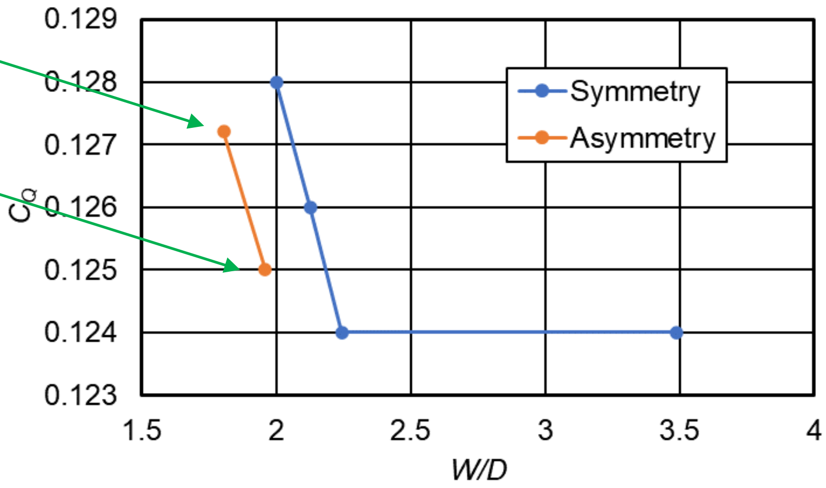
Aircraft width vs Torque coef. (Hovering)

Aerodynamics are evaluated using CFD (rFLow3D ©JAXA)

Overlap 0.2D

Overlap 0.04D



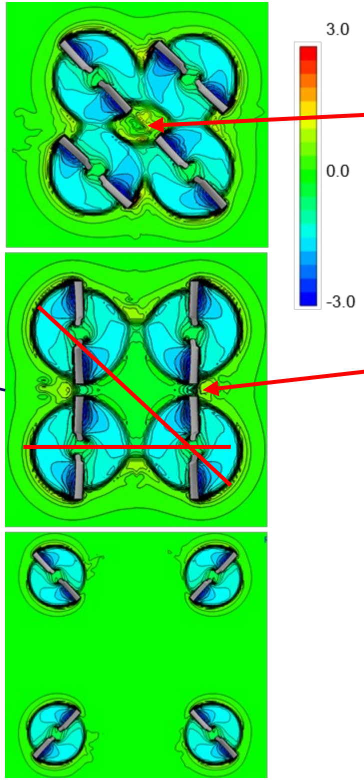
- Asymmetric configuration results in a higher efficiency (lower torque).
- Negative effect is small when overlap is small on rotating planes.
- Inter-rotor interference can be more harmful when propellers are placed on the same plane.

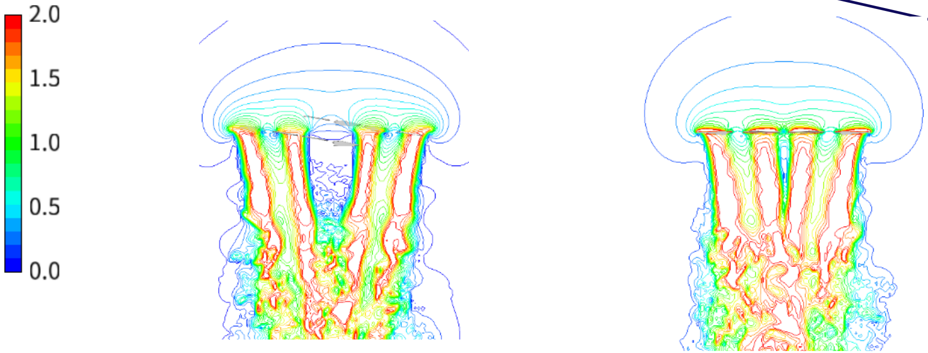
Torque coef. vs Aircraft width at thrust coef. CT＝0.0108

rFLow3D
Accuracy in descritization:
  4th order in convective terms
  2nd order in viscous terms
Unsteady simulation by LU-SGS implicit scheme
Overlap mesh system was used

Observation of Flows around Symmetric Config.

CT＝0.0108
CQ=0.126
Blade angle＝9.26°





Diametrical cross section

Cross section through adjacent propeller axes

Normalized velocity magnitude for middle W/D

Normalized axial velocity for various W/D

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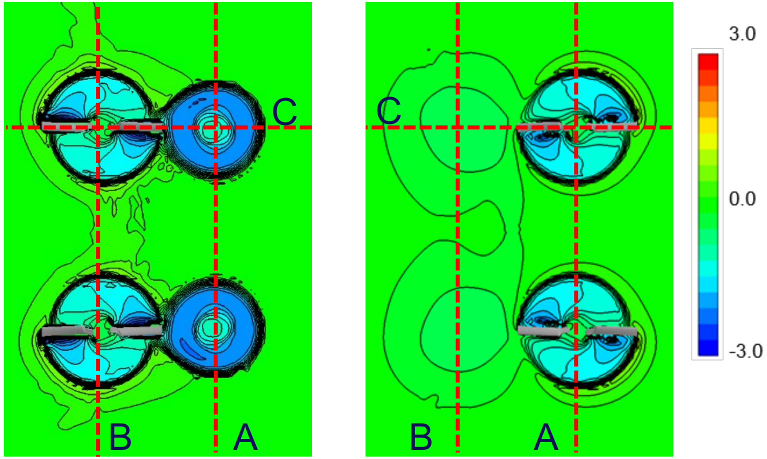
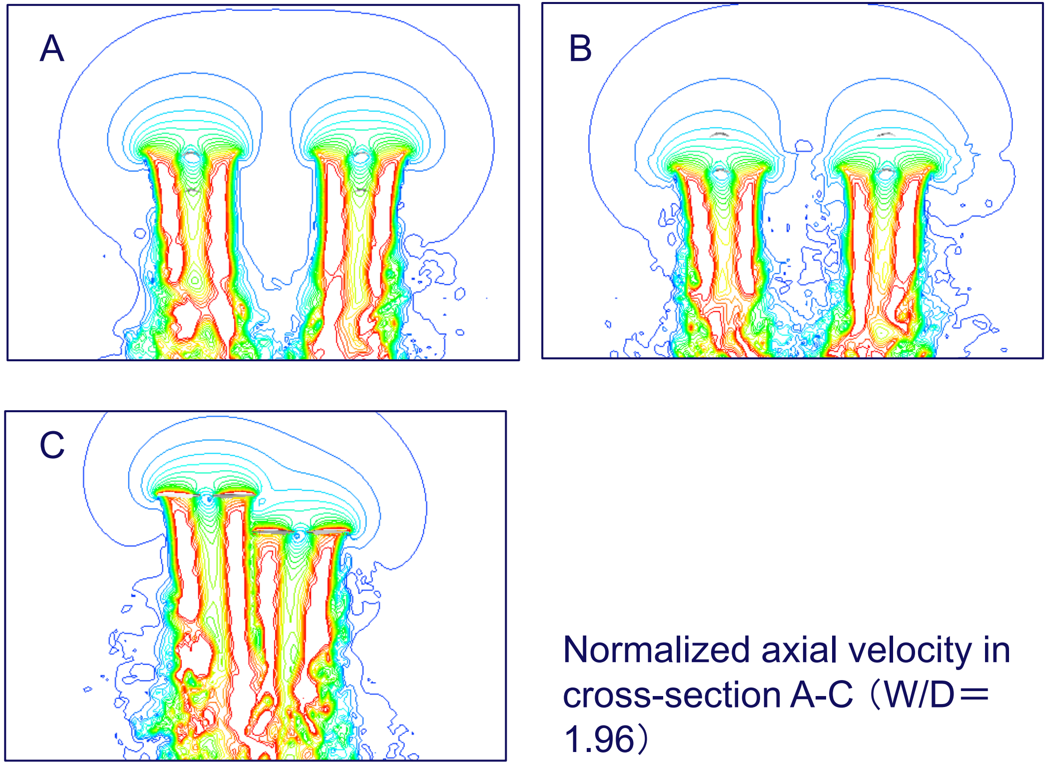
Observation of Flows around Asymmetric Config.



Lower rotational plane

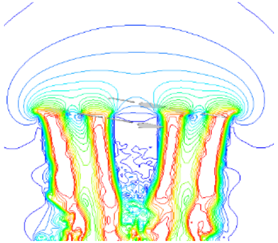
Upper rotational plane

Normalized axial velocity in rotational plane（W/D＝1.96）



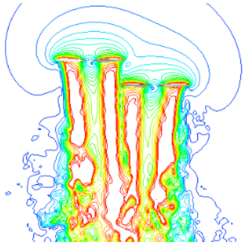
Normalized axial velocity in cross-section A-C（W/D＝1.96）

Observation of Flows around Asymmetric Config.



	C_T	C_Q	θ
W/D	2.24		
ALL	0.0108	0.126	9.26

Symmetric config.



	C_T	C_Q	θ
W/D	1.96		
Upper	0.0108	0.127	9.27
Lower	0.0108	0.123	9.04
Ave.	0.0108	0.125	9.16

Asymmetric config.

Upper rotor：
Aerodynamic loss increases
- Interaction between front/rear rotor is small
- Suction flow due to lower propeller induces loss on the upper rotor.

Lower rotor
Aerodynamic loss decreases
- Interaction between front/rear rotor is small
- Downwash from the upper rotor suppress the blade tip vortex and loss.

Propeller interaction effect between the left and right rotors is dominant. Propeller interaction effect between the front and rear rotors is small due to longer distance.

Conclusion

- A drone for unmanned inspection of headrace tunnels of hydraulic power station was developed.
- High maneuverability and robustness of sensing and navigation systems are confirmed by carrying out fully autonomous flight demonstrations in highly disturbed environments.
- An asymmetric aircraft configuration for flying through narrow tunnels was designed and its aerodynamic characteristics were investigated.
- The rotor efficiency increases by overlapping the rotating planes less than 25%.

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