IROS 2015

Aerial Tool Operation System using Quadrotors as Rotating Thrust Generators

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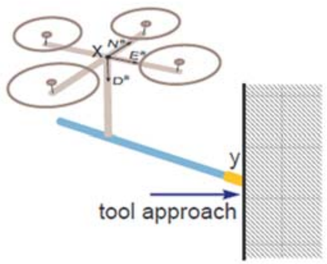
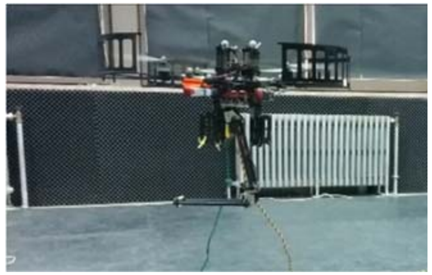
Aerial manipulation

- Promising applications require
  - Physical interaction with environment
  - Certain level of dexterity



Tool operation
SNU, Automatica 2015

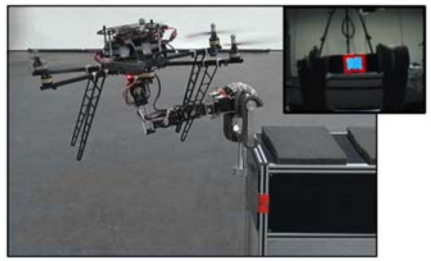
Transportation
UPenn, RSS 2013



Drone manipulator
SNU, ICRA 2015

1DOF grasp
Yale, TRO 2014

Object manipulating
UPenn, DARS 2013

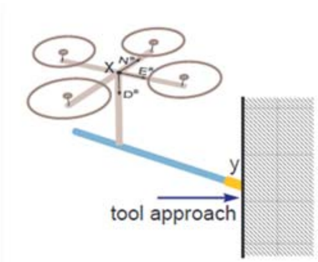


Operating drawer
SNU, ICRA 2015

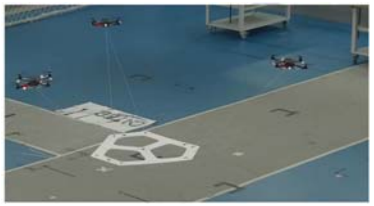
Aerial manipulation

- Systems designed for aerial manipulation

Helicopter + gripper
Pounds at el, Yale., TRO 2014

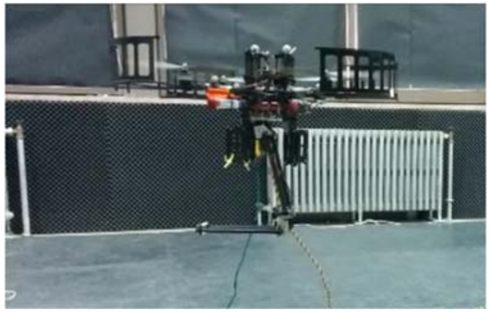


Quadrotor + rigid tool
Nguyen at el, SNU, Automatica 2015



Quadrotor + cable
Cortes et al, LAAS/CSIC-UPC, RSS2013

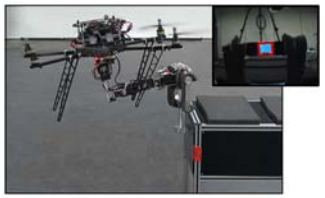
UAV + Arm



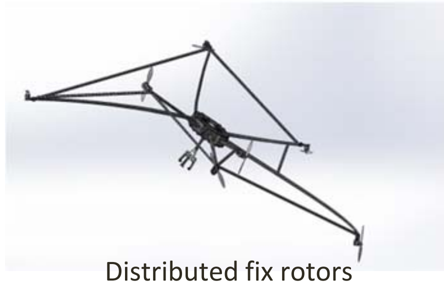
Yang at el, SNU, ICRA2015

Thomas at el., Upenn, ICRA2014

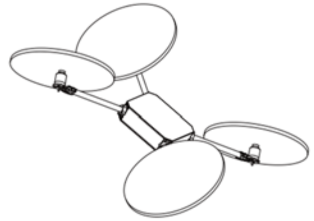
Garimella at el., JHU, ICRA2015



Kim at el., SNU, ICRA2015



Distributed fix rotors
Nikou at el., NTUA, ICRA2015



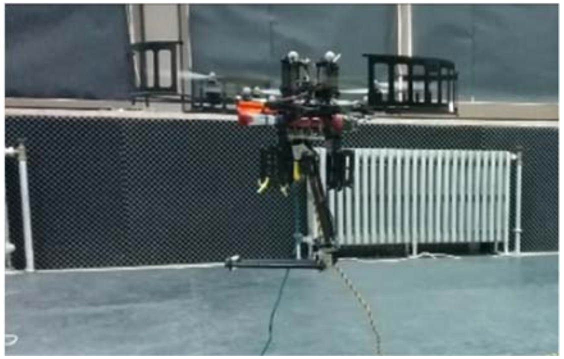
Quad Tilt Rotor
Oosedo at. El, Tohoku, ICRA2015

Tilted Propellers
Rajappa at. El, CNRS, ICRA2015

UAV-Arm system is the most popular aerial manipulation system

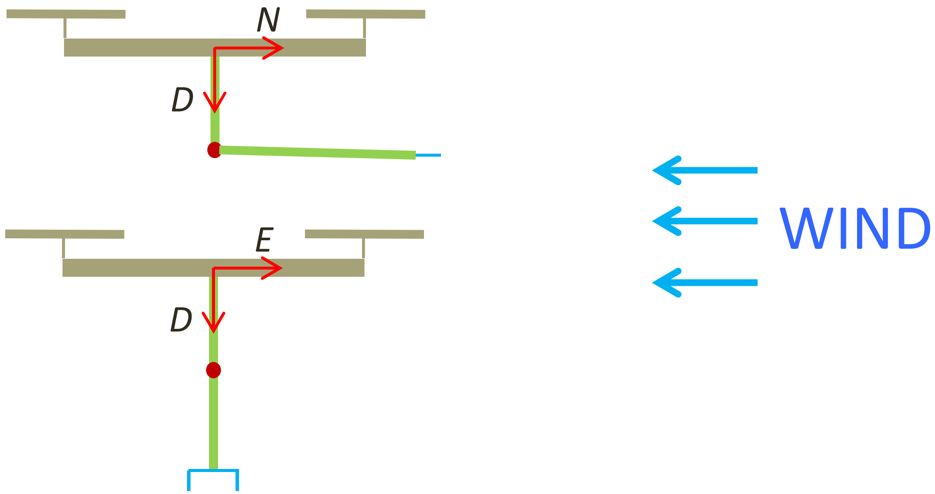
UAV - Arm

- Limitations
  - Limited payload/flight-time
  - Under-actuation



Yang at el., SNU, ICRA2015

- Asc. Pelican (650 g/ 16 min.)
- 2DOF arm 400g
- Task: 1.5 N, 16 min.



UAV - Arm

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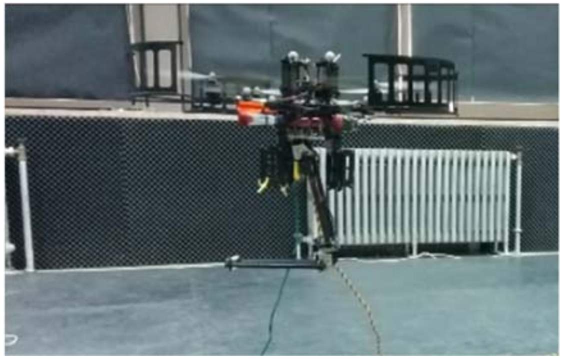
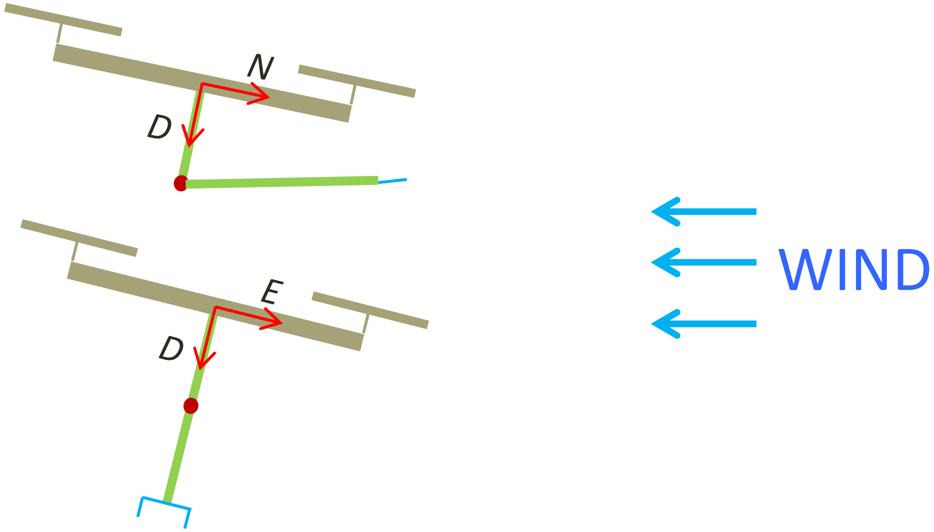


Yang at el., SNU, ICRA2015



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UAV - Arm

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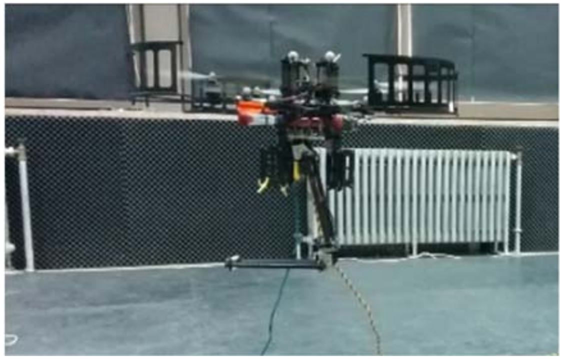


Yang at el., SNU, ICRA2015

- Asc. Pelican (650 g/ 16 min.)
- 2DOF arm 400g
- Task: 1.5 N, 16 min.

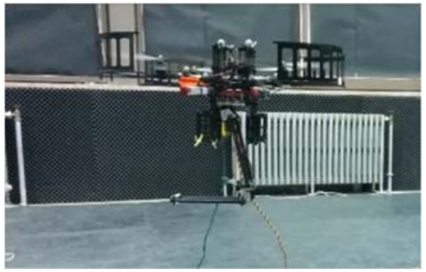
7-DOF arm, DLR

7-DOF arm, Arcas

X Payload
X Complex coupling

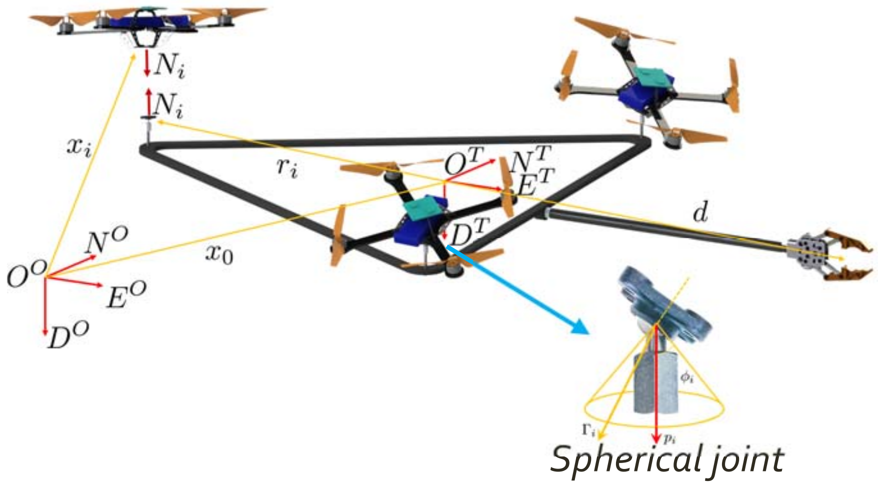
Contribution

- New aerial manipulation system
  - Multiple quadrotors + simple un-actuated tool by spherical joints
  - Spherically-connected multiple-Quadrotor Tool System (SmQT)



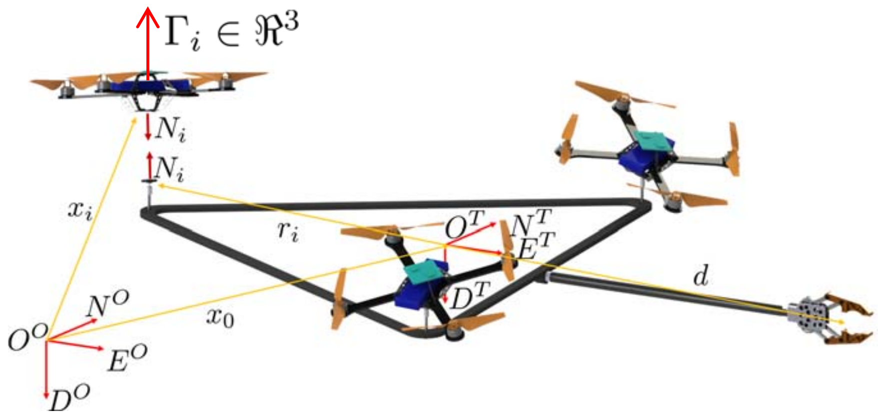
Yang at el., SNU, ICRA2015

7-DOF arm, Arcas



✓ Resolve payload and under-actuation
✓ Model joint limit in the form of constrained optimization
✓ Modular construction

System dynamics



- **6-DOF Tool dynamics**

$$M\dot{\xi} + C + G = U + F_e$$

tool control input — external force

$\xi := [\dot{x}_0, \omega_0] \in \Re^6$: tool translate/angular velocity

$\omega_i \in \Re^3$: quadrotor angular velocity

$R_0, R_i \in SO(3)$: tool and quadrotor attitude

$\Gamma_i = \lambda R_0^T R_i e_3 \in \Re^3$: thrust in fixed frame

- **3-DOF Quadrotor attitude dynamics**

$$J_i \dot{\omega}_i = -S(\omega_i) J_i \omega_i + \tau_i$$

decoupled from tool dynamics — torque input

- **Tool control input**

$$U = \bar{R} B \Gamma$$

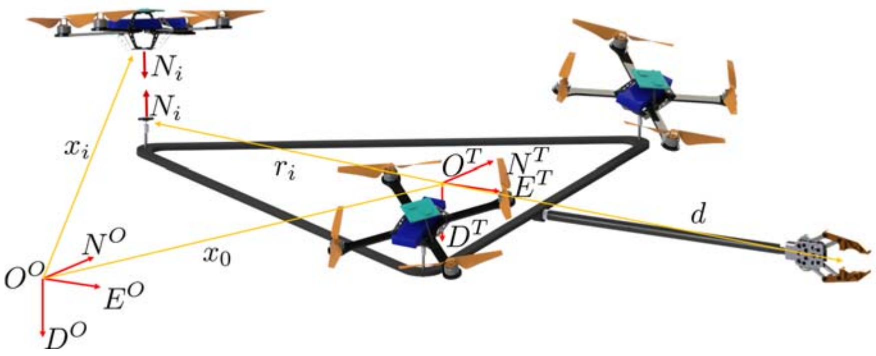
quadrotor thrusts as control actions

$$\Gamma := \begin{bmatrix} \Gamma_1 \\ \Gamma_2 \\ \cdots \\ \Gamma_n \end{bmatrix} = \begin{bmatrix} \lambda_1 R_0^T R_1 e_3 \\ \lambda_2 R_0^T R_2 e_3 \\ \cdots \\ \lambda_n R_0^T R_n e_3 \end{bmatrix} \quad \bar{R} := -\begin{bmatrix} R_0 & 0 \\ 0 & I \end{bmatrix}$$

$$B := \begin{bmatrix} I & I & \cdots & I \\ S(r_1) & S(r_2) & \cdots & S(r_n) \end{bmatrix}$$

➡ Use quadrotors as thrusters to control the tool dynamics

Control decode



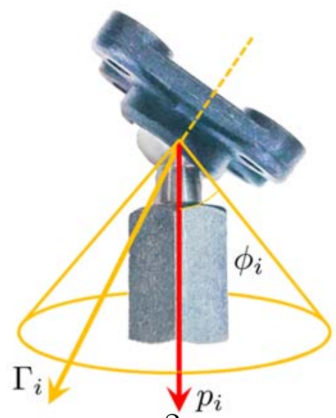
- **Generate control input**

$$B\Gamma = \bar{R}^T U \qquad B := \begin{bmatrix} I & I & \dots & I \\ S(r_1) & S(r_2) & \dots & S(r_n) \end{bmatrix} \qquad \bar{R} := -\begin{bmatrix} R_0 & 0 \\ 0 & I \end{bmatrix}$$

$\Rightarrow$ Find $\Gamma = [\Gamma_1; \Gamma_2; \dots; \Gamma_m] \in \Re^{3m}$ for given $U_d \in \Re^6$

- **Spherical joint limit** (p_i, ϕ_i)

$$p_i^T \Gamma_i \geq |\Gamma_i| \cos\phi_i$$



$p_i \in S^2, \phi_i \in \Re$

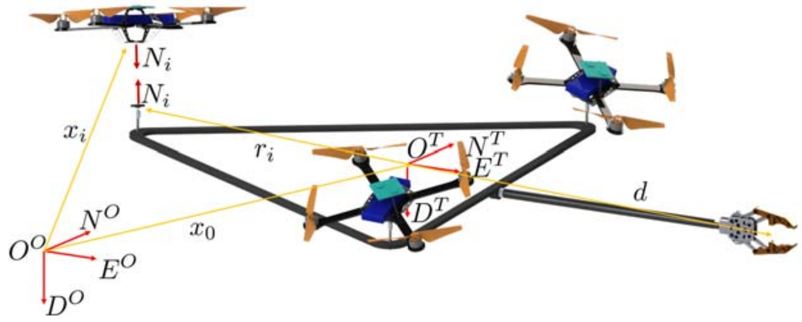
- **Optimal control allocation**

$$\min_{\Gamma_1, \Gamma_2, \dots, \Gamma_n \in \Re^3} \frac{1}{2}\Gamma^T\Gamma$$

$$\text{subject to} \quad B\Gamma = \bar{R}^{-1}U$$ ← generate desired tool control

$$p_i^T \Gamma_i \geq |\Gamma_i| \cos\phi_i$$ ← respect the spherical joint constraint

Solution existence



$$\min_{\Gamma_1,\Gamma_2,\ldots,\Gamma_n \in \Re^3} \frac{1}{2}\Gamma^T\Gamma$$

$$\text{subject to} \quad B\Gamma = \bar{R}^{-1}U$$ ← generate desired tool input

$$p_i^T\Gamma_i \geq |\Gamma_i| \cos\phi_i$$ ← respect the spherical joint constraint

Generate desired tool wrench

$$\text{"fully-actuated" iff } \mathrm{rank}(B) = 6$$

$$B\Gamma = \begin{bmatrix} I & I & I \\ S(r_1) & S(r_2) & S(r_3) \end{bmatrix} \begin{bmatrix} \Gamma_1 \\ \Gamma_2 \\ \Gamma_3 \end{bmatrix}$$

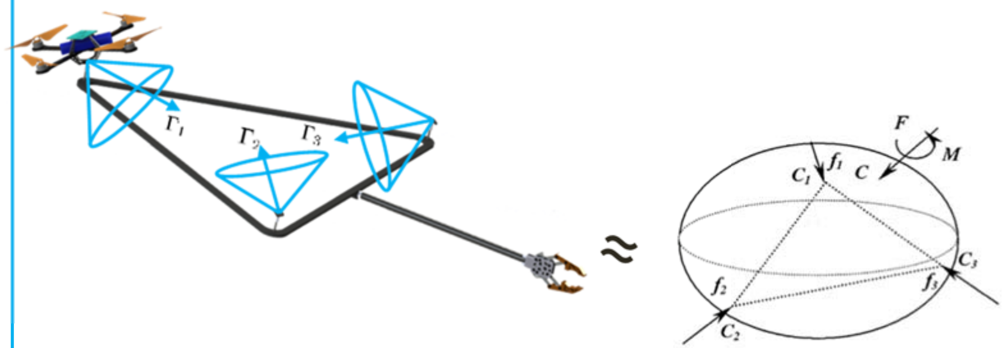
$$B = \begin{bmatrix} I & 0 \\ S(r_1) & I \end{bmatrix} \begin{bmatrix} I & 0 & 0 \\ 0 & S(r_2 - r_1) & S(r_3 - r_1) \end{bmatrix} \begin{bmatrix} I & I & I \\ 0 & I & 0 \\ 0 & 0 & I \end{bmatrix}$$

$$\mathrm{rank}(B) = 6 \leftrightarrow (r_2 - r_1) \times (r_3 - r_1) \neq 0$$

Prop. 1: 6-DOF tool fully-actuated iff at least three quadrotors are used with their attaching points r_i not collinear.

Respect the spherical joint constraint

"force-closure"

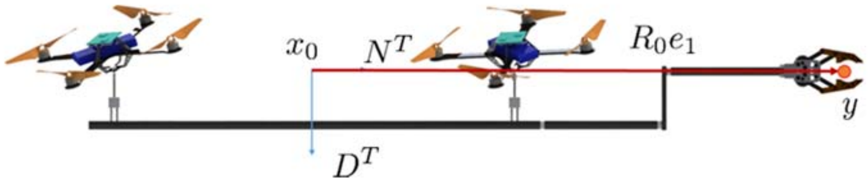


tool is in "force-closure" with Γ_i (Li at el. IEEE-TRA 2003)

Prop. 2: For fully-actuated tool system, any desired tool wrench can be generated under spherical limit, iff thrust actuations make force-closure.

J.-W. Li, H. Liu, and H.-G. Cai, "On computing three-finger force-closure grasps of 2-D and 3-D objects," IEEE Transactions on Robotics and Automation, vol. 19, pp. 155-161, 2003.

S2QT system



- **Control objective** $(y_d, \gamma_d) \in \Re^3 \times S^2$

$$(y, R_0 e_1) \to (y_d, \gamma_d)$$

Assumptions

- Not fully-actuated, not in force-closure
- $d \times (r_2 - r_1) = 0,\ \tau_e \approx 0$
- 5-DOF actuation

- **Kinematics relation**

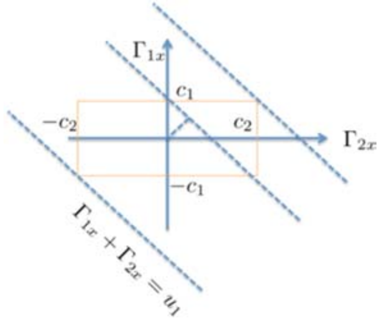
$$y = x_o + R_o d \to \dot{y} = \dot{x}_o + R_o S(\omega_o) d$$

consider as a virtual control

- **Lyapunov function**

$$V_1 = \frac{1}{2} e_y^T e_y + \frac{1}{2}\sum_{i=1}^{2} m_i \dot{e}_x^T \dot{e}_x + \frac{1}{2}\omega_0^T \left(J_0 - \sum_{i=1}^{2} m_i S^2(r_i)\right)\omega_0 + k_R(1 - \gamma_d^T R_0 e_1)$$

$y \to y_d$ $\quad \omega_0 \to 0$ $\quad R_0 e_1 \to \gamma_d$



- **Control allocation**

$$\min_{\Gamma_1, \Gamma_2 \in \Re^3} \frac{1}{2}(\Gamma_1^T \Gamma_1 + \Gamma_2^T \Gamma_2)$$

subject to $\begin{bmatrix} I & I \\ S(r_1) & S(r_2) \end{bmatrix} \begin{bmatrix} \lambda_1 R_0^T R_1 e_3 \\ \lambda_2 R_0^T R_2 e_3 \end{bmatrix} = \begin{bmatrix} F_d \\ M_d \end{bmatrix}$

$$p_i^T \Gamma_i \geq |\Gamma_i| \cos\phi_i$$

Closed-form solution exists if

$$|F_{dx}| < c_1 + c_2$$

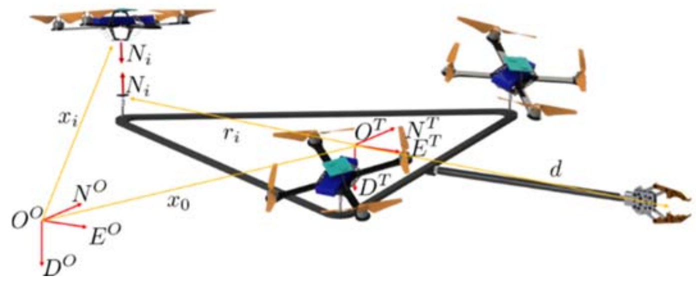
$$c_i = \frac{1 - \cos^2\phi_i}{\cos^2\phi_i}\Gamma_{iz}^2 - \Gamma_{iy}^2 > 0$$

Thm. 1: For Γ_i calculated as above, $(y, R_0 e_1) \to (y_d, \gamma_d)$ asymptotically.

SmQT system

- **Control objective** $(y_d, R_d) \in \Re^3 \times SO(3)$

$$(y, R_0) \to (y_d, R_d)$$



- Fully-actuated, in force-closure
- Tool full 6-DOF actuated

- **Kinematics relation**

$$y = x_o + R_o d \to \dot{y} = \dot{x}_o + R_o S(\omega_o) d$$

consider as a virtual control

- **Lyapunov function**

$$V_2 = \frac{1}{2} e_y^T e_y + \frac{1}{2} \begin{bmatrix} \dot{e}_x^T & \omega_0^T \end{bmatrix} M \begin{bmatrix} \dot{e}_x \\ \omega_0 \end{bmatrix} + k_R (3 - \mathrm{trace}(R_0^T R_d))$$

$y \to y_d$ $\quad$ $\omega_0 \to 0$ $\quad$ $R_0 \to R_d$

- **Control allocation** *(convex - Boyd at. el. TRO 2007)*

$$\min_{\Gamma_1, \Gamma_2, \ldots, \Gamma_m \in \Re^3} \frac{1}{2} (\Gamma_1^T \Gamma_1 + \Gamma_2^T \Gamma_2 + \ldots + \Gamma_m^T \Gamma_m)$$

subject to $B\Gamma = W_d$

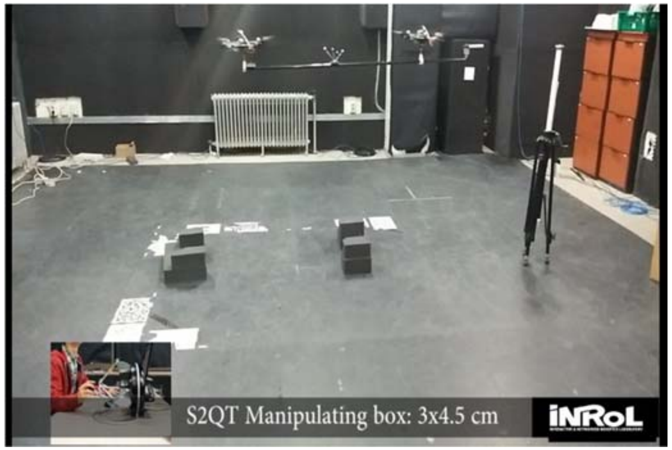
$$p_i^T \Gamma_i \geq |\Gamma_i| \cos \phi_i$$

Thm. 2: For Γ_i calculated as above, $(y, R_0) \to (y_d, R_d)$ asymptotically.

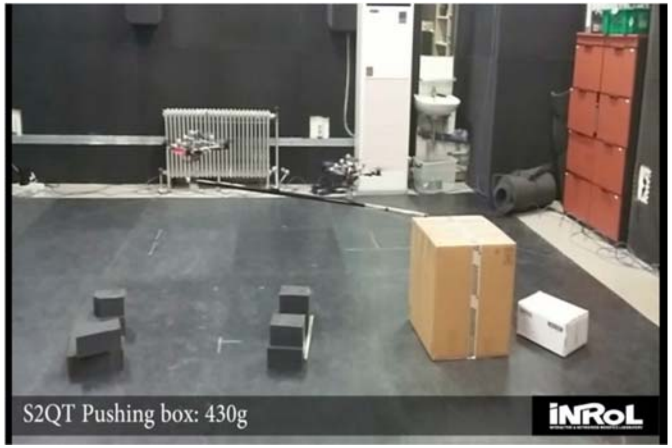
S. P. Boyd and B. Wegbreit, "Fast Computation of Optimal Contact Forces," IEEE Transactions on Robotics, vol. 23, pp. 1117-1132, 2007.

Experimental results

- Prototype
  - AscTec. Hummingbirds (200 g, 20 min.) max thrust of 20N
  - S2QT tool of 340 g S3QT tool of 430 g
  - Joint limit 32 deg



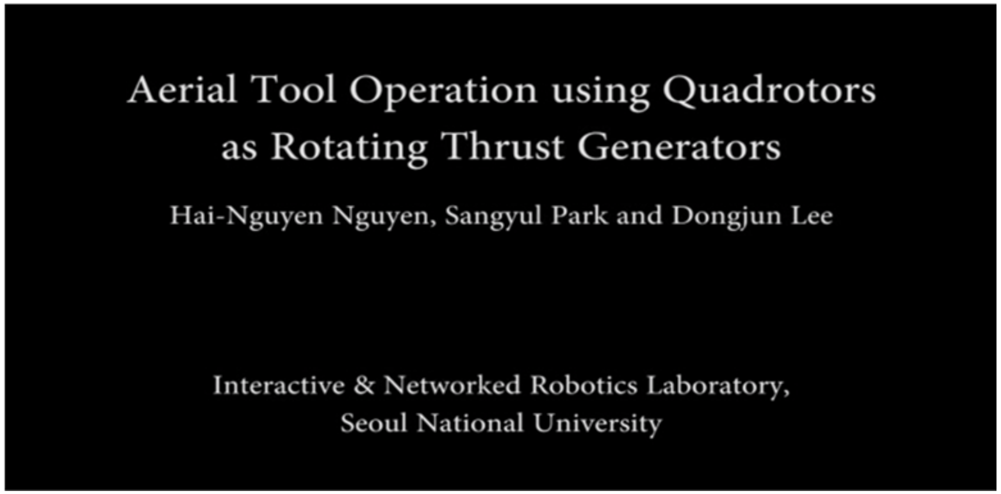
Impedance control
max contact force of 14N

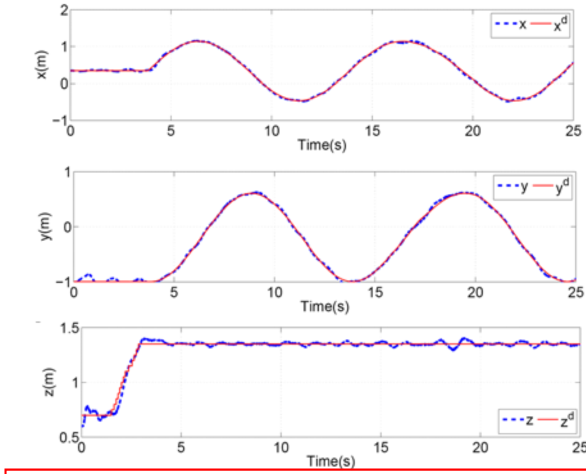


Full 5DOF motion
tracking error of 5cm

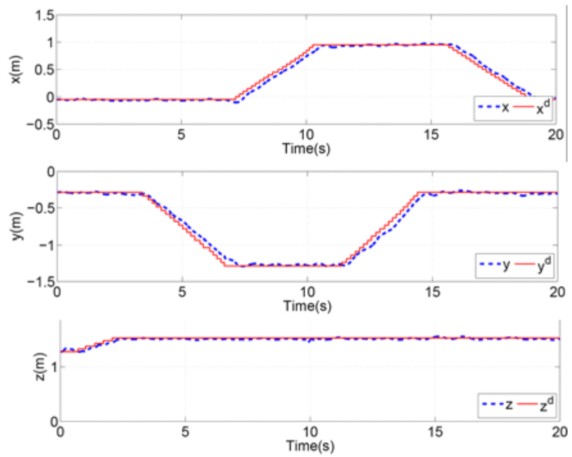
More scenarios: http://inrol.snu.ac.kr/iros2015

Experimental results





S2QT pose control(error < 5cm)



S3QT pose control (error < 7cm)

More scenarios: http://inrol.snu.ac.kr/iros2015

Conclusion

Spherically-connected multi-Quadrotor Tool System (**SmQT System**)

- SmQT system
  - Increase payload/interaction force by utilizing multiple off-the-shelf quadrotors
  - Resolve under-actuation configured to meet task requirements
- Future work
  - SmQT as stationary airbase for robotic arm

Thank you

for your attention!