Cooperative aerial load transportation / Areal manipulation

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1 Motion planning

Swarms in general Medina et al. (2020)

Taking the appropriate formation Vasarhelyi et al. (2014) Soria et al. (2020)

Collective decision making Yu et al. (2010)

Nature inspired Gelblum et al. (2015)

Trajectory

Slalom Loianno and Kumar (2018)[1]

Altitude modification Loianno and Kumar (2018)[2]

Obstacle avoidance Lee et al. (2018)[3] offers a total framework for stable flight with obstacles. Spurny et al. (2019) which carries rod-shape load between obstacles in real environment. Loianno and Kumar (2018) slalom path

Algorithms

Rapidly-exploring Random Tree LaValle (1998) Spurny et al. (1998) The proposed method uses a stochastic optimization with the aim to find a solution in which the states with distance between the UAVs close to the desired one are preferred which increases reliability and efficiency of the cooperative carrying task.

[1] `https://www.youtube.com/watch?v=Ilrb_P-8od4` Time 1:13
[2] `https://www.youtube.com/watch?v=Ilrb_P-8od4` Time 0.58
[3] `https://www.youtube.com/watch?v=kX1qzZJPmcE`

2 Attachment type

Cable suspension

From different points Michael et al. (2009) discusses lifting a triangle with three drones. Masone et al. (2016) which discusses a cube suspended from different points by cables connected to multiple drones. Mohiuddin et al. (2020b) Jiang and Kumar (2013) inverse kinematics of a triangle. Sreenath and Kumar (2013)

From single point Jackson et al. (2020) Guerrero et al. (2015)[4] Mohammadi et al. (2020) [5] Mohammadi et al. (2018) Garcia de Marina and Smeur (2019) Erskine et al. (2019) [6] Thapa et al. (2019) Xie et al. (2020)

Rigidly attached Mellinger et al. (2010) Loianno and Kumar (2018) Tagliabue et al. (2017)[7] Mellinger et al. (2010)[8] Nguyen et al. (2015)[9] with round, spherical connectors.

3 Payload shape

Shape un-aware Tagliabue et al. (2017) Mellinger et al. (2010)

Rod-shaped Tagliabue et al. (2017) Tagliabue et al. (2017)'s first experiment is performed by such tubes. Gassner et al. (2017) Bandala et al. (2018) Wu et al. (2020) Mohiuddin et al. (2020b) which also covers un-equal load [10]. Spurny et al. (2019) Lee et al. (2018)[11]

Regular polygon in both Tagliabue et al. (2017) and Tagliabue et al. (2017), the system is shape-unaware. Jiang and Kumar (2013) inverse kinematics of a triangle. Sreenath and Kumar (2013)

Cylinder Mohammadi et al. (2018)

Cube Masone et al. (2016)

[4] urlhttps://www.youtube.com/watch?v=TQ9O4UVHmJM
[5] https://www.youtube.com/watch?v=TQ9O4UVHmJM,https://www.youtube.com/watch?v=aQ9rBlenekU
[6] https://www.youtube.com/watch?v=rOCvd4uHFV4
[7] https://www.youtube.com/watch?v=QvjyDV8sNPo
[8] https://www.youtube.com/watch?v=YBsJwapanWI
[9] https://www.youtube.com/watch?v=lAYUR7LpDEU
[10] https://www.youtube.com/watch?v=o2K4BWfRGHk&t=219s
[11] https://www.youtube.com/watch?v=kX1qzZJPmcE

4 Formation control

Centralized Nguyen et al. (2015)

Using motion capture systems

Decentralized

Leader follower Tagliabue et al. (2017) Tagliabue et al. (2017) Gassner et al. (2017) Loianno and Kumar (2018) Wu et al. (2020) Chen and Shan (2019) Xie et al. (2020) follower only uses its IMU information derived from cable's force which connects it to the leader.

Leaderless Mohammadi et al. (2018); Mohammadi et al. (2020) Rezaee and Abdollahi (2017)

5 Communication

Explicit Each robot, uses other robots measurements. Loianno and Kumar (2018)[12] Masone et al. (2016) Spurny et al. (2019)[13][14] the planning task is realized onboard of one of the robots and the obtained trajectories are shared (using Wi-Fi in the presented HW setup) with its neighbor to ensure reliable coordination of the system.

Implicit Implicitly by sensing the internal forces of the robots acting on the transported object Tagliabue et al. (2017) Tagliabue et al. (2017) Gassner et al. (2017)[15] Wu et al. (2020) [16] Thapa et al. (2019)

No communication Mohammadi et al. (2018); Mohammadi et al. (2020) uses a motion capture camera to coordinate.

6 Energy aware

Mohiuddin et al. (2020b)

[12] https://www.youtube.com/watch?v=Ilrb_P-8od4
[13] https://www.youtube.com/watch?v=Pdg3j791I9c&feature=youtu.be
[14] https://www.youtube.com/watch?v=FQH769AnYbQ&feature=youtu.be
[15] https://www.youtube.com/watch?v=8pFBufXOumw
[16] https://www.youtube.com/watch?v=ib9IxCNAVPs

7 Surveys

Chung et al. (2018) Coppola et al. (2020) Villa et al. (2019) discusses particularly load transportation with multi-rotor UAVs Ruggiero et al. (2018) discusses exclusively Areal manipulation Tuci et al. (2018) also discusses exclusively areal transportation. Mohiuddin et al. (2020a) also discusses exclusively areal manipulation for both single and multiple agents.

8 Environment

Static

Dynamic Spurny et al. (2019) Alonso-Mora et al. (2017)

9 Grasping

Magnetic Loianno and Kumar (2018) Mellinger et al. (2010)

friction-based

Penetration based

Spherical joints Tagliabue et al. (2017)

10 Projects

Ollero et al. (2018)

11 Others

12 Per paper

Spurny et al. (2019)

- **Motion planing** The environment is not dynamic. That is obstacles are already known and the motion is already planned.
  - **Probabilistic Roadmaps (PRM)**: LaValle (1998)
  - **Rapidly Exploring Random Trees (RRT)**: Kavraki et al. (1996)
- **Communication** Wifi
- GPSS for localization

Loianno and Kumar (2018)

- **Sensors**:
  - IMU
  - Camera
- **Covers**
  - Estimation
  - Control
  - Trajectory planning
- **Key contributions**
  - a new approach to coordinated control, which allows independent control of each vehicle while guaranteeing the system's stability
  - a new cooperative localization scheme that allows each vehicle to benefit from measurements acquired by other vehicles

Tagliabue et al. (2017) Highlights

- Multiple MAVs mechanically coupled.
- Uses spherical joints
- doesn't require force/torque sensors
- decentralized
- doesn't rely on communication between agents and can be easily extended to multiple MAVs
- spherical joint, which guarantees attitude decoupling among agents and payload
- kinetically constraints the translational dynamic of each agent to be the same as the motion of the payload
- The task of the master is to lead and steer the group of vehicles connected to the payload towards a desired destination, while keeping a constant transportation altitude.
- The slaves are not aware of the destination goal, but share the same altitude of the master, assisting their leader in the transportation task.
- Cooperation and coordination of the slave agents with respect to the movements of the master is achieved via re- shaping the apparent physical properties of each slave, in order that maximum compliance to the actions of the master is guaranteed.

- modify the inertial properties of each slave MAV to make it behave as a **passive point-mass**, accelerated by any interaction force applied on it and subject to viscous friction directly proportional to its own velocity. This new behavior can be achieved by means of **admittance control**.
- The key idea behind admittance control is that a **position-controlled mechanical system** can achieve arbitrary interaction dynamics by sensing the force coming from the environment and by accordingly generating and following a reference trajectory. In order to do so, every slave agent is equipped with a force estimator, which senses the force applied by the master to the payload. This force information is then used by the admittance controller to regulate the position of the slave agent, so that it guarantees maximum possible compliance to the estimated force.
- In a collaborative transportation maneuver, the master MAV agents behaves as if it was carrying the payload alone, pulling it towards the desired goal while keeping a **constant altitude**. For this reason it only executes its on-board **reference tracking feedback loop**. The reference trajectory which leads it to the destination goal can be provided by a user or by an on-board or off-board planning system.
- Information is instead shared via the payload itself, which is used as a medium to transfer the interaction force applied by the master to the slaves. This information flow is mono-directional, from the master to the slaves, as the slaves fully act according to the sensed force applied by the master on the transported structure, while the master executes its standard reference tracking algorithms.
- agents (a) do not have to agree on a **global inertial reference frame**
- do not need to share the destination goal. This is made possible by the fact that each slave on-line generates a reference trajectory in the same frame as the external forces are estimated. The destination goal has to be known only by the master and, as a consequence, has to be expressed in the master's reference frame only.
- the agents can grasp the payload in such a way that its weight force can be equally distributed among the agents.

Reaching the transportation altitude / taking off and landing

- A centralized Finite State Machine (FSM) sends altitude increment commands Δh to both the agents and make sure they both fulfill the command.

Agents low level architecture

State estimator

Position and attitude controller

Slave-specific control architecture

Force estimator

- Force estimates can be obtained from the sole inertial information provided by the on-board IMU and the state estimator
- combined with the measurement of the rotational speed of the rotors

Admittance controller generates an on-line reference trajectory (position, velocity, attitude and angular velocity) for the position and attitude controller, given the estimate of the external force.

13 Academic events

Conferences

Journals

- Journal of advanced transportation [17]

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[17] `https://www.hindawi.com/journals/jat/`

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