Summary of Literature Survey

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# A Roadmap for US Robotics: From Internet to Robotics (2016)

Due to an increase in manufacturing jobs, sales of robot systems for manufacturing are increasing. Human-robot collaboration is developing. It is necessary to develop the following techniques further: sensor capabilities, manipulation, autonomous navigation, user-friendly interfaces.

Key areas of focus:

* Control and Planning: task and motion planning under uncertainty; “hardware design language”-style interfaces between specification and deployment; optimization for constrained environments; manipulation complexity; scaling up and accommodating uncertainty in dynamic environments; multi-agent coordination, including heterogeneous agents.
* Human-Robot Interaction: making interfaces more complex and more user friendly; perceiving, modelling and adapting to humans; sociability; adaptation to work complexity and variety; robot-mediated communication; shared control; long-term interaction phenomena; safety standards.
* Multi-agent Robotics: distributed control and decision-making; mixed centralized and decentralized information exchange (what needs to be shared?); human-swarm interaction; heterogeneous networks; communications and sensing.

Remarks:

A general overview of the field. It was useful for learning about the overarching issues affecting multi-agent robotics, especially concerning information exchange.

# Guest Editorial: Can Drones Deliver?, d’Andrea(2014)

This provides the rationale for drone delivery and an estimation of delivery cost using state-of-the-art technology for a given payload size and range.

Future work is identified for the following areas:

* Design: drones must be efficient, reliable, tolerant of diverse conditions and able to hover.
* Localization and Navigation: GPS is not adequate for reliability, working in different operating conditions and in changing environments. Low-cost sensors and positioning solutions are needed.
* Coordination for common resource usage (e.g. charger stations)
* Managing public reactions, government regulations and privacy concerns

Remarks;

The discussion about future work is relevant for any drone solution; in future work try to build in robustness to operating environment conditions and avoid reliance on GPS.

# A Survey of Quadrotor Unmanned Aerial Vehicles, Gupte et al. (2012)

This paper provides an overview of the state of the art in UAV flight:

* An introduction to the characteristics of UAVs, their control inputs and their advantages over manned AVs
* The technique of flying, common configurations and typical high-level system structures
* Control systems and dynamic models:
  + Innovations in sensor miniaturization
  + Challenges in controlling quadrotors due to under-actuated dynamics, but PID techniques work well
  + Most research focuses on micro-quadrotors
  + Control strategies can be motivated by nature
  + Must adapt to different environmental parameters such as wind and terrain
* Sensors:
  + Inertial measurement unit sensor (accelerometer for orientation with respect to Earth; gyroscope for rate of rotation around axes)
  + Distance sensors, e.g. ultrasonic ping sensor, infrared, laser range finder; these are used for low-level altitude control and obstacle avoidance
  + To complement the IMU: barometer (for altitude), magnetometer (for direction)
  + GPS for tracking and localization
  + Camera: video feedback, image recognition, obstacle avoidance
* Vision systems:
  + LIDAR is impractical for miniature quadrotors
  + UAV vision systems can be used for object detection and tracking, position estimation, navigation and landing
  + Systems can use onboard cameras (monocular/binocular) or ground-based tracking
* Navigation:
  + Map-based navigation, localization in unknown environments
  + SLAM algorithms for offboard systems require consideration of 3D space
  + Testbed systems (e.g. STARMAC, RAVEN)
* Applications:
  + Search and rescue (good for multi-agent systems), emergency response
  + Military use: search and destroy, surveillance, border patrol
  + Climate monitoring
* Future work: efficient powering, path planning, SLAM, takeoff and hover stabilization.

Remarks:

This was a comprehensive introduction to the field, more relevant to the Project’s scope than the US Robotics Roadmap. It provides evidence that PID techniques have been used for controlling quadrotors on several occasions. There are constraints placed on powering and navigation capabilities.

# Toward a Fully Autonomous UAV, Tomic et al. (2012)

A comprehensive design for an autonomous UAV with a limited payload, onboard processing and decision-making.

* Requirements;
  + Modularity, flexibility with respect to sensing and planning
  + Operation in unstructured indoor- and outdoor-environments (therefore no GPS)
  + Robust flight capabilities due to changing wind conditions
  + Onboard processing and decision-making
  + Mission-specific recognition
* New framework:
  + Reliable flight and navigation
  + High-level functions (object perception, failsafe operation, online mission planning)
* SLAM approaches:
  + Send laser scan data offboard for processing (for pose estimates, planning), keep control and platform stabilization onboard
  + Laser-based onboard SLAM for indoors
  + Monocular visual onboard SLAM for indoors and outdoors
  + Pose estimate from SLAM + IMU data feed into the EKF, which provides a full state estimate for controllers
  + The new approach: two sensors for indoor and outdoor flight respectively, avoid SLAM. This needs stereo processing, visual odometry, laser odometry and computer vision.
* Software framework:
  + Low-level components (data fusion and flight control)
  + High-level components (situational awareness, mission planning)
  + Functions can also be divided into Perception, Cognition and Action
* Perception:
  + Indoor environments: clearly defined vertical structures, poor lighting and few features. Use laser scan odometry.
  + Outdoor environments: no clear structures, IR wavelengths present in sunlight, more natural features and good lighting. Use visual odometry.
  + Combine the two approaches to compensate for each sensor’s drawbacks
  + Use a stereo camera for object detection from above and for odometry
  + Odometry data can give relative position and orientation information, but have measurement and processing latencies slower than quadrotor dynamics; therefore use an indirect feedback Kalman filter.
  + Recognition needed for 2D patterns, house detection with stereovision and object detection with lasers.
* Action:
  + Full-state feedback tracks a reference pose, velocity and acceleration
  + High-level components can choose between different flight modes for each path segment: preparation, powered off, landed, takeoff, flying, landing, failsafe. Activate and initialize components as needed.
* Cognition:
  + Break down mission control tasks into atomic states corresponding to basic functionalities
  + An example of detecting and using a window-based exit
* Hardware used in the implementation and experimental results
* Conclusion and future work
  + Reactive collision avoidance at low-level
  + Miniaturization, reduce weight and sensor size
  + Microsoft Kinect can be used for depth images, but relies on artificial IR light, therefore suitable for indoors only.
  + Integrate GPS into data fusion
  + Multi-agent cooperation

Remarks;

Of relevance to the Project are the high-level design requirements, comments on sensors for odometry, comments on flight modes and mission control tasks. The presentation of the design process in this paper is comprehensive and methodical, so use this as inspiration for the technical section of the report. In designing the controller, consider their breakdown of mission control tasks.

# Cooperative Path-Planning for Autonomous Vehicles Using Dynamic Programming, Flint et al. (2002)

* Introduction: this paper formulates a decision-making process for cooperative control among a team of UAVs, using dynamic programming
* Vehicle assumptions: constant velocity, avoid collisions with other UAVs, impose a maximum turning angle, communication uses imperfect wireless channels
* Environment assumptions: each UAV has a map but we can’t assume each UAV has the same map
* Goals
  + Move through the environment to uncover the most information about the environment as a team
  + Local UAV must plan local path to reach the global goal
  + Discretize in time by making decisions at discrete time intervals
  + Discretize in space by making limited number of choices per step
  + Vehicle lifetime is limited by fuel capacity
  + There is diminishing marginal utility of covering a search area
* Dynamic programming
  + Discrete-time stochastic control
  + Limited lock-ahead policy makes problem tractable but is sub-optimal
  + Include a utility function to convey information beyond the planning horizon
  + Vehicles can no longer predict others’ positions, so introduce a random variable to represent loss at time *k+q* due to interference from other vehicles
* Results:
  + A lawnmower technique works best when no *a priori* information about the environment is available
  + The proposed DP approach achieves faster decrease in average uncertainty when *a priori* information is available
  + At path intersections we reduce the gain of low-angle choices to maximize coverage and thus information acquired

Remarks:

Not entirely relevant for cooperative transport, but the use of a cost function / gain function associated with the environment can feed into decision making.

# A Distributed Framework for Real Time Path-Planning in Practical Multi-Agent Systems, Shamma et al. (2017)

* Introduction:
  + Motivation – capture the flag game
  + The players in each team must be able to compute their trajectories over the given time horizon based on their local information at each decision time
  + They should be able to update their strategy based on the moves of the opposing players
  + Previous techniques described by others has been either simple and intractable with higher dimensions (Flint et al.), or computationally-efficient and centralized (linear programs).
  + Model Predictive Control involves solving an optimization problem for a finite time horizon
  + Usually agents must communicate whole trajectories between neighboring agents, thus increasing communication cost and latency. Approximate the linear program with something for distributed computation.
  + Each defender solves a local version of the linear program based on the current location of neighboring agents and attackers. Optimization occurs up to the prediction horizon. A linear feedback law drives attackers toward the flag.
  + Framework testing:
    - Existing algorithms are tested offline in MATLAB, with agents modeled as point masses with single/double integrator dynamics. This is useful for stability analysis and convergence property observation, but gives no insight about actual behavior under real agent dynamics, hardware constraints or communication losses.
    - V-REP simulator is used for a detailed quadrotor model
    - The attacker’s controls have a human in the loop.
* Problem formulation:
  + Find the state, evolution of the state, inputs, cost function as a function of state and time
  + The algorithm considers only neighborhood information; agents can sense locations of neighbors or communicate once for location information
  + Reduced communications may lead to defenders occupying the same sector, so basic collision avoidance is needed
* Simulation metrics: optimality, execution time, quantity of required communication
* Hardware testing: each MatMAV instance executes an algorithm for each quadrotor (<mzahana.gitbooks.io/matmav-guide/content>)
* Future work: outdoor tests, onboard implementation, vision-based algorithm to identify attackers, collision and obstacle avoidance

Remarks:

This is slightly more relevant for cooperative transport, with useful insights into the prototyping process. The problem formulation is very applicable to the Project: there are directions on which variables to focus on, performance metrics and rationale for their use of software packages.

[Testing with double integrator dynamics in MATLAB] is useful for stability analysis and convergence property observation, but gives no insight about actual behavior under real agent dynamics, hardware constraints or communication losses.

# Distributed Real Time Control of Multiple UAVs in Adversarial Environments: Algorithm and Flight Testing Results, Shamma et al. (2018)

This builds on their previous paper, Shamma et al (2018). The algorithm is implemented as a C++ class, using GLPK. A ROS C++ node interfaces between the class and ROS environment. The multi-agent simulation uses software in the loop. Hardware is as per the RISC bootcamp.

Remarks:

This is the direct inspiration for the Project; the scope of the Project is a different application for the hardware / software platform used in these RISC lab papers.

# Dynamic Collaboration without Communication: Vision-Based Cable-Suspended Load Transport with Two Quadrotors, Gassner et al. (2017)

* Introduction
  + Context: object transportation in unknown GPS-denied environment
  + Orientation control via quadrotor attitude control and cable connection
  + Collaborative transport achieved without explicit communication (using leader-follower approach), and there is model and control of the quadrotor’s whole dynamics (not just hovering)
  + Overview of hardware setup
* Methodology
  + Equations of motion
  + Leader control scheme: uses LQR
  + Follower control scheme
  + Trajectory planning
  + Compensating for drift and alignment
* Experimental setup
  + Hardware setup: an April tag attached to the back of the leader lets the follower track it
  + Software setup
  + System evaluation: a task is specified
  + Leader tracking evaluation: initialize the follower in the wrong direction; observe how the follower adapts to a varying leader altitude
* Results

Remarks:

This is a good example directly relevant to the Project’s objectives. The hardware used is very similar to what is available in RISC Lab, and incorporates monocular Apriltag detection for tracking the leader. The idea of a leader and follower is intuitive. The leader uses LQR control, but PID control can be attempted. Mocap infrastructure is required for the evaluation stage and this is available at RISC Lab. For further consideration: reorienting the leader and follower to compensate for wind drag; using multiple drones (who would be the leaders and the followers?).

# A Flying Inverted Pendulum, Hehn, d’Andrea (2011)

* Introduction
* Dynamics: equations of motion for quadrotor, inverted pendulum; Lagrangian mechanics; dynamics of the two combined
* Nominal trajectories to be followed by the quadrotor, linearized dynamics for each controllable parameter
* Controller design: LQR controllers for *x-r, y-s*, separate controller for vertical direction
* Experimental results

Remarks;

This was cited in Gassner et al. for its formulation of dynamics. In section V, it states:

The two horizontal degrees of freedom are single-input, five-state systems. The vertical degree of freedom is a single-input, two-state system. Although simpler design methods exist for such systems, LQR is used to make the results easily transferable to the design for a circular trajectory.

Reverse-engineering and reconstructing Gassner at al. will be difficult. Investigate implementing a subset of Gassner by simulation of the flight dynamics using PID controllers. Investigate and understand Lagrangian mechanics equations.

# Cooperative Manipulation and Transportation with Aerial Robots, Michael et al. (2010)

* Introduction:
  + Section 2: conditions for static equilibrium in 3D;
  + Section 3: three-robot system configurations for aerial manipulation;
  + Section 5: designs and validates controllers that comply with the model;
  + Section 6,7: review and analyze simulation and experimental results
* Problem formulation: mechanics of a cable-suspended load, cooperative manipulation with three aerial robots.
* Mechanics of 3D manipulation with cables: robot positions for desired payload pose; hovering robots; finding positions that meet kinematic constraints and stable equilibrium for payload. The leader-follower approach here uses computer vision, UV and PID control (no payload)
* Stability analysis and study of potential energy
* Experimentation: quadrotor robot control signals’ derivation; controller-design equations, payload model and experimental setup
* Results: cooperative lifting, cooperative pose manipulation and transport, a potential field controller is used to avoid robot collisions
* Planning multirobot manipulation and transportation tasks

Remarks;

If pursuing the idea of a leader-follower approach, problem formulation and stability analysis is needed anyway. The constraints 1-4 on page 75 concerning flight dynamics should be used and stated explicitly in the problem formulation. They use a PID approach so this derivation can inspire controller design for the Project.

# Cooperative Grasping and Transport Using Multiple Quadrotors, Mellinger et al. (2013)

* Introduction:
  + Section 2: literature review
  + Section 3: model for one / multiple quadrotors rigidly attached to a payload
  + Section 4: robot control laws defined with respect to a payload to stabilize the payload along 3D trajectories
  + Section 5: design of gripping mechanism
  + Section 6: experimental results
* Literature review: Michael et al. look at aerial manipulation using cables; this paper focuses on using grippers
* Dynamic model: define coordinate systems (world, body), including with respect to each quadrotor, rotation matrix for body to world transform, angular velocities, position vector to a reference point (here: the center of mass), motor model, equations of motion
* Control: basis vectors, attitude (optimizing a cost function), hover control, trajectory control in 3D (PID feedback using position and velocity error, linearization and inversion). This decentralized control law could be centralized:

The state estimates can be combined to create a single estimate of the state of the entire body … this averaging reduces the noise on the state estimate of the entire body and thus results in a cleaner control signal

* Gripping mechanism description
* Results: experimental setup, mass and inertia parameters, use of different hovering setups, trajectory tracking and velocity measurements
* Conclusion:
  + Summary of investigation
  + Future work: a gripper design for passive engagement, autonomous system identification methods for multiple quadrotors picking up payloads with unknown masses and moments of inertia

Remarks:

The paper deals with a slightly different problem (using a gripper). Nonetheless the comments on centralization impacting quality of control signal merit consideration. The model derivation is clearer in section 3.

# Cooperative Transportation Using Small Quadrotors Using Monocular Vision and Inertial Sensing, Loianno, Kumar (2018)

* Introduction:
  + design, control, planning and estimation for cooperative transport of rigid structures with quadrotors using one camera and one IMU.
  + Mellinger et al. use linearized controllers and need external Mocap for state estimation
  + Gassner et al. use vision-based cable-suspended cooperative transport
  + This paper looks at the model and control of vehicle system with magnetic attachments to a structure, inference of localization and optimizations due to the setup’s rigid structure, combining the transportation and localization problem
* Modeling and control: dynamic model, position and attitude structure controllers, motor speeds mapping (quadratic optimization)
* State estimation: localization with respect to an inertial frame
* Motion refinement
* Experimental results: experimental setup, camera used for pose estimation and is pointed downwards

Remarks:

The authors consider a rigid setup of multiple quadrotors, which is used to infer localization and allow for a novel combination of localization and transportation. This is likely to be unfeasible for large or bulky payloads, hence should not be used in the Project. Include a clear architecture overview, like the diagram in Figure 3.

# Introduction to the Special Issue on Aerial Manipulation, Ruggiero et al. (2018)

* Introduction:
  + applications, technical problems (operations in close proximity, under-actuation of UAV, unstable dynamics, aerodynamic effects, dynamic effects due to presence of object),
  + future work (energy, safety, regulation)
  + limitations of testing in research lab environments
* Outline of special issue topics: single-arm aerial manipulation, dual-arm aerial manipulation, cooperative aerial manipulation

Remarks:

A very recent survey of state of the art in cooperative transport. Lee et al. look at estimating online the weight and inertial properties of an unknown payload, building an adaptive controller, and obstacle avoidance.

# Aerial Co-Manipulation With Cables: The Role of Internal Force for Equilibria, Stability, and Passivity, Tognon et al. (2018)

* Introduction:
  + high level overview of problem, aerial manipulation via cables, decentralized algorithms, need for limiting explicit communication, proposal overview and stability analysis results
  + Section 2: model derivation
  + Section 3: control strategy, system equilibrium
  + Section 4: stability of equilibrium
  + Section 5: passivity and stability of transportation
  + Section 6: simulation results
  + Section 7: conclusion
* System modeling: frames of reference, dynamics equations for two robots and load, control problem
* Control design and equilibria: admittance filter equations, closed loop system equilibrium configurations, equilibria inverse problem, equilibria direct problem
* Stability of equilibria: proofs of stability using LaSalle’s principle
* Passivity and Stability of Manipulation
* Numerical validation: results of simulation provided in a detailed technical report
* Conclusion: future work involves testing in the lab, generalization to N robots and general loads (not just beams)

Remarks:

This is directly relevant to the Project, with the desired setup and clear derivations. These should be followed closely. Consult the technical report for guidance on implementation in MATLAB.

# Multi-objective control for cooperative payload transport with rotorcraft UAVs, Gimenez et al. (2018)

* Introduction:
  + Context: previous techniques have used a non-linear H∞ controller, iterative LQR optimal controller, analytic algorithms derived using dialytic elimination, geometric controller, particle swarm optimization with PID tuning. In the presence of wind perturbations: adaptive fuzzy theory, Lyapunov technique.
  + Proposal: a null-space controller
  + Section 2: define the problem
  + Section 3: variable definition
  + Section 4: control analysis
  + Section 5: dynamic models
  + Section 6: simulation
  + Section 7: conclusion
* Problem formulation: geometry, priority hierarchy
* Variable definition: the formation, the payload, obstacles, orientation
* Controller: translating objectives to equations, task conflicts, stability analysis, tuning
* Simulation testbed / dynamic models: wind and floor collision, model equations
* Simulations: testbed architecture diagram, parameters table
* Conclusions

Remarks:

There is a wide listing (but not comparison) of previously-used control algorithms provided in the context of the problem. The benefits of using null-space theory are unclear, but it seems it’s used to execute competing control objectives (e.g. wind disturbance rejection, obstacle avoidance). Section 1.2 outlines control objectives which should be included in the design specification for the Project. Section 2 contains a hierarchy of objectives which can also be included in the design specification and the problem formulation. Include a parameters table when discussing simulation models.

# Fast Mutual Relative Localization of UAVs Using Ultraviolet LED Markers, Walter et al. (2018a)

* Introduction
  + Context; issues with previous solutions (need strong lighting conditions, large markers, limited space, computational complexity
  + State of the art and its issues (moving from outdoors to indoors, unknown environments, scaling up, infrastructure reliance);
  + Previous attempts with acoustic noise, RGB cameras
* Theoretical background: UV markers and sensors, intensity of UV decays in glass, so use 395 nm
* Hardware overview: grayscale camera, fisheye lens, UV bandpass filter, UV LEDs
* Methodology: system ID, camera calibration, spot size; directional vector estimation and distance estimation using image distance of two markers, full pose estimation
* Experiments: distance estimation based on spot size, bearing vector estimation precision, neighbor distance from mutual distance of points, outdoor experiments of mutual localization of two UAVs
* Conclusion: intended use is in swarm control, stabilization of UAV formations in arbitrary environments.

Remarks: This is a viable technology that could be useful for the Project, if inter-agent localization is needed. There are not many details about the software implementation and it may be too involved to emulate this system in the time available.

# Mutual Localization of UAVs based on Blinking Ultraviolet Markers and 3D Time-Position Hough Transform, Walter et al. (2018b)

* Introduction: context, existing issues, previous research, innovations
* Theoretical background: UV spectrum, 3D time parametrization, Hough Transform
* Algorithm for origin-point position and blinking frequency tracking: base algorithm (image pre-processing, Hough space operations, origin-point retrieving, blinking frequency retrieval), improvements (weighted Hough space, pre-computed masks)
* Experimental validation: setup, indoor validations, outdoor validations, blinking frequency estimation, comparison with state of the art
* Conclusion: lower computational power needed, can encode extra information via blinking patterns, high reliability outdoors.

Remarks:

Understanding this paper requires a strong understanding of visual geometry and signal processing; it will be difficult to emulate this in the time available. Localization is not the goal of the Project, cooperative transport is. Include a table of main parameters:

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Meaning | Impacts on | Experimental value [unit] |
|  |  |  |  |

# Aggressive optimal control for agile flight with a slung load, De Crousaz et al. (2014)

Cited by sources 8 and 16.

* Introduction: optimize a cost function using optimal control (model-based) or reinforcement learning (sample-based). This author has previously combined the two methods.
  + This paper: the hybrid approach is scaled to deal with a quadrotor with a slung load. To perform dynamic tasks the quadrotor uses mode switching.
* Related work:
  + grippers add extra weight, reduce agility
  + cables allow agility but increase degree of under-actuation
  + model- and sample-based methods have been used to reduce energy of a suspended load’s oscillations
  + design process has been optimized and applied to reference trajectories
  + This paper: optimize the whole controller, using the state space
* Problem definition:
  + Statement of degrees of freedom
  + Hybrid system of modes, physical model (rigid body and point mass)
  + Optimal control algorithm: iLQG with initial trajectory given by LQR controller
  + Cost function
* Tasks and results: waypoint task (follow a figure 8 path), learning agile tasks with potential mode switches (e.g. moving through a narrow window)

Remarks:

This paper focuses on one quadrotor with a slung load. Look at the problem definition and the formulation of the physical model.

# Unified motion control for dynamic quadrotor maneuvers demonstrated on slung load and rotor failure tasks, De Crousaz et al. (2015)

Cited by sources 8 and 20.

* Abstract: use an iterative optimal control algorithm to derive controllers and generate trajectory
* Introduction:
  + UAV multirotor: useful for aggressive maneuvers, acrobatics, manipulation, transportation of slung loads
  + This paper: general control algorithm, change the underlying system dynamics model and cost function for each task
  + System dynamics vary significantly; systems are non-linear, highly underactuated and unstable, so non-linear control needed
  + Sequential Linear Quadratic control: a time-indexed feedforward and feedback control law
* Relevant work: as per source 18, also considers rotor failure responses
* Contributions: use of SLQ (=iLQG without multiplicative noise) requires only a new system model and cost function to generate control policies
* System dynamics for quadrotor without load, quadrotor with load.
* Optimal control algorithm: discussion of trajectory optimization methods, SLQ
* Task cost function derivation
* Results for the window task, narrow window task, single rotor failure, double rotor failure (opposite)
* Conclusion, future work – implement on hardware using an MPC strategy

Remarks:

This work follows on from source 18, with no new information about slung load transport. Future work may benefit from adopting this approach, but see an evaluation of this approach in source 20.

# Mixed integer quadratic program trajectory generation for a quadrotor with a cable-suspended payload, Tang, Kumar (2015)

Cited by source 8.

* Introduction:
  + gripper versus cable suspension, focus on load stabilization and load swing minimization, little attention to fast and aggressive load maneuvering
  + This paper: consider trajectories with large load swings, periods of zero cable tension when load is in temporary freefall
  + Hybrid dynamical system:
    - quadrotor with load, cable is taut and quadcopter in control of load
    - quadrotor only, load undergoes projectile motion
  + This paper: model trajectory planning for the whole system in obstacle-filled environments
  + Related work in trajectory optimization, including source 18: QP, MIQP, MIQCQP, iLQG
  + This paper: explicit constraints on obstacle avoidance, maximum velocity and acceleration, motor inputs
* Dynamics and control: dynamics for the two system states, “guards” and “resets”
* Trajectory generation framework: differential flatness, MIQP formulation
* Problem formulation: waypoint constraints, obstacle avoidance constraints, hybrid system
* Trajectory planning algorithm:
  + 3 steps: initial load trajectory planning, refine load trajectory, generate corresponding quadrotor trajectory
  + Further considerations: complexity of decision vector size, algorithm choice (branch & bound versus oversampling), partitioning over regions and solving trajectories separately
* Numerical results: obstacle avoidance, hybrid trajectories
* Experimental results: setup, obstacle avoidance, load pickup and release with hybrid trajectories
* Conclusions: future work – speed up computation, stabilize hybrid system, apply to multi-agent system, iterate over each segment of trajectory

Remarks:

A comprehensive look at the slung-load problem for one quadrotor. Relevant aspects: hybrid dynamical system, problem formulation, methodology.

# An integrated framework for cooperative aerial manipulators in unknown environments, Lee et al. (2018)

Cited by source 14.

* Introduction:
  + Previous research in cooperative aerial transportation, tow cables, multi-DoF grasping arms – coordination issues, uncertainties
  + This paper: parameter estimator and controller designed without force-torque sensors, analysis and simulation to test estimations under noisy measurements, smooth path generation with automatic trajectory updating, implementation with aerial manipulators
* Decentralized dynamics: aerial manipulator dynamics, payload dynamics, combined dynamics with a rigid grasp
* Cooperative framework:
  + estimation and control: model-based state and mass estimation with a consensus algorithm and adaptive controller
  + path planning: trajectory generation of each aerial manipulator with unilateral constraints, kinematic coordination to generate trajectory of each end effector, motion generation with task priority
  + obstacle detection and avoidance
* Experiments: two aerial manipulators carry an unknown payload, hardware setup and experimental results
* Conclusion: proposed method can be made more precise and robust than direct adaptive control

Remarks:

The authors chose grippers over tow cables, a decentralized and cooperative framework. The derivations require advanced maths and control strategies.

# Geometric control of quadrotor UAVs transporting a cable-suspended rigid body, Lee (2014)

Cited by source 16.

* Introduction:
  + aerial transport by towed cables, applications,
  + related work- minimize load swinging (not suitable for agile load transportation); geometric non-linear control systems for one quadrotor with cable-suspended load and many quadrotors transporting a common payload cooperatively (that source assumes that the payload is a point mass)
  + This paper:
    - construct a control system for arbitrarily-many quadrotors connected to a rigid body payload via rigid links
    - coordinate-free form of motion equations using Lagrange mechanics on a non-linear manifold
    - geometric control system with a rigid body payload exponentially tracking position and attitude
    - explicit inclusion of coupling effects between dynamics of payload, cable and multiple quadrotors into the system
* Problem formulation: Lagrangian mechanics, equations of motion, tracking problem
* Control system design for simplified dynamic model
  + Ignore attitude dynamics for each quadrotor, assume thrust at each quadrotor can be chosen arbitrarily
  + Choose parallel components of control inputs ui|| so that payload follows desired position and attitude trajectory, and desired direction of each link qid
  + Choose normal components uiͱ so that actual direction of links qi follows qid
  + Design parallel components
  + Design normal components
* Control system design for full dynamic model: quadrotor attitude, tracking error, stability analysis
* Numerical example:
  + parameter values, path to follow, initial conditions
  + Monitored parameters: actual maneuver trajectory, tracking errors for load position and attitude, link directions, quadrotors’ attitude; tension and control inputs

Remarks;

The maths is complicated. Relevant sections include the problem formulation, the assumptions for a simplified dynamic model in section 3 and the numerical simulation’s methodology in section 5.

# Self Motion and Wind Velocity Estimation for Small-Scale UAVs, Zachariah, Jansson (2011)

* Introduction:
  + Need for data on self-motion, external conditions in GPS-denied environment
  + Want to estimate self-motion of UAV, direction and speed of UAV; use 3 orthogonal anemometers to measure air speed with respect to sensor frame
  + Estimation problem: given ***d = v-w***, separate ***v, w***
  + No design considerations for anemometer placement
  + Previous source uses a downward directed monocular camera, processes data to estimate ***v***. Assumes parallel motion over level ground; robustness and drift not explored.
  + This paper: use natural static points detected using IMU + forward directed camera + common feature point extraction algorithm. Some drift errors but system can separate ***v, w***
* Process model:
  + discrete time system models for wind and UAV navigation states
  + wind velocity; navigation error states; visual memory states
* Measurement model:
  + States in the process models are correlated through measurement of ***d*** and a set of visual epipolar points
  + Anemometers measure velocity with respect to surrounding air
  + Visual memory and epipolar point processing
* State estimation framework
* Simulations:
  + wind generated using a vector-AR(L) process
  + estimation setup
  + user-defined trajectory set in a navigation frame
* Conclusions: heading drifts but the estimates can be separated in the air speed data

Remarks:

The goals are relevant. The modeling is complicated and there are no design considerations for anemometer placement.

# Quadrotor UAV for Wind Profile Characterization, Moyano Cano (2013)

* Summary
  + Considers the use of UAV quadrotors to measure wind profiles in offshore wind farms without dedicated sensors for wind characterization
  + Algorithm relates tilt angle of the vehicle to local wind speed and direction
  + Algorithm for computing wind speed and direction is derived from dynamic pressure equation, wind direction derived using trigonometry
  + Method 1: wind speed estimated with only angles from flight controller
  + Method 2: dynamic linear equations describing behavior of quadrotor used to estimate wind speed with dynamic effects
  + Method 3: estimate wind speed with Lineal Kalman Filter
  + Data is compared with measurements from a ground-mounted anemometer
* Limitations: all three methods ignore sensor noise, physical properties are assumed
  + Method 1: no dynamic effects therefore wrong estimates for transients
  + Method 2: affected by accelerometer noise, so must LPF signals first
  + Method 3: untested with transients
  + Comparison with anemometer used 5-minute averages, not 1Hz time series, so poor time resolution and unknown transient behavior
* Future work: use of multiple quadrotors to generate 3D wind profile using virtual grid

Remarks:

This dissertation provides a comprehensive methodology and clear derivations. The setup doesn’t need an anemometer.

# Wind Speed and Direction Detection by means of Solid-State Anemometers Embedded on Small Quadcopters, Bruschi et al. (2016)

* Abstract: application of a compact MEMS-based 2D anemometer to estimate quadrotor air speed. Correcting for ground speed provided by internal GPS and inertial units, wind speed estimation is possible
* Introduction:
  + Previous work: accurate wind velocity estimation onboard by modeling vehicle pitch as function of air speed, corrected for ground speed using GPS
    - Low directional accuracy, requires accurate dynamical model
  + Add airflow sensor to IMU and do sensor fusion
  + Pitot tubes are a sensor candidate, but they need to be placed in the direction of the wind vector, difficult for rotary UAVs which are multidirectional
  + This paper: equip quadrotor with new 2D wind sensor – small size, low power consumption and acceptable accuracy
* Results:
  + Calibration of anemometer in improvised wind-tunnel, anemometer then mounted above the plane of rotors on a quadrotor, then testing in a full-size wind-tunnel
  + Resulting wind speed and direction measurements suggest propellers only have a significant effect on estimated wind speed below 10 m/s and negligible effect on angle data for 6 < ***v*** < 20 m/s

Remarks:

The paper contains important considerations for design of wind speed measurement systems. The use of specialized equipment may make replication infeasible.

# A rotor-Aerodynamics-Based Wind Estimation Method Using a Quadrotor, Song et al. (2018)

* Introduction:
  + applications for wind data
  + drawbacks of using anemometer
  + non-anemometer methods and drawbacks: GPS + EKF + UKF, decomposition, deviation from a preset path, dynamics of quadrotor without rotor aerodynamics, model wind resistance versus quadrotor inclination angle
  + This paper: use aerodynamic model of rotors to estimate wind speed by calculating thrust of quadrotor and hardware in the loop simulation
* Dynamic model and control of quadrotor: parametrization for coordinates; PID controller used for waypoint control, attitude controller uses PD control
* Wind estimation method: direction, speed
* Experiments and results
  + Setup, HILS used to keep quadrotor in place
  + Calibration equipment
  + Verification tests
* Conclusion: HILS with 3D force sensor used to partially simulate quadrotor’s full DoF motion; acceptable accuracy of wind estimation; now they need better controllers, disturbance observer

Remarks:

The survey of the field and technique is relevant for the Project but the experimental setup can’t easily be replicated (a lot of specialist hardware).

# Wind Data Collection Techniques on a Multi-Rotor Platform, Wolf et al. (2017)

* Introduction: motivation for collecting wind data with UAVs, accounting for noise introduced by vehicle dynamics
* Problem formulation:
  + Design requirements
  + Previous research: effects of downwash, low quality data at low air speeds, use of UAV’s tilt compensation to determine wind speed and direction
* Design methodology: focus on getting reliable measurements
  + Method 1: analysis of anemometers’ suitability for UAVs
  + Method 2: analysis of feedback from UAV flight parameters to get wind speed and direction
  + Anemometer characterization: comparison of price, weight, type; experimental evaluations of noisiness, outdoor trials for bias checking, bias modeling
  + Rotor airflow analysis: identifying zones of lowest disturbance versus distance from center of quadrotor
  + Correlation of flight behavior to wind speed and direction: correlation exists but experimentally they couldn’t determine relationship precisely
* Design review and evaluation: proposed design based on previous considerations
* Recommendations and future work: using cheaper sensors for wind direction determination; further investigation into effects of mounted sensors on UAV

Remarks:

The format, remit and methodology are all relevant. This is a work in progress, they still haven’t correlated UAV pitch and roll with wind speed and direction.

# Measuring Wind with Small Unmanned Aircraft Systems, Prudden et al. (2018)

* Abstract:
  + application of UAVs;
  + discussion of different UAV configurations (including multi-rotor UAVs);
  + discussion of methods for measuring airflows using UAVs;
  + results from a quadrotor-mounted Multi Hole Pressure Probe
  + Feasible to measure mean wind velocity and turbulence intensity from hovering aerial platform with good high spatial resolution
  + Discussion of future UAV technological- and operational deployments with respect to wind engineering applications

Remarks:

Section 2 provides thorough consideration for rotorcraft UAV setups. Section 3 is a very comprehensive survey of efforts in the field of multirotor UAV wind measurement. It would be worth rereading these sections for an overview of design considerations and limitations of the state of the art in UAV anemometry.

Further examination:

* Introduction and objectives:
  + Description, applications, configuration types for UAVs
  + Atmospheric Boundary Layer: description, measurement techniques (buildings, wind turbine sites are inadequately served by masts), drawbacks of LIDAR, Power spectral density of ABL
  + Use UAVs due to tolerance of flights <1hr long, ability to traverse entire height of ABL, carry sensor payloads, use less infrastructure than manned aircraft
  + Fixed-wing platforms: high endurance, long range; Good for upper reaches of ABL, Bad for continuous measurements at specific locations
  + UAVs can be used for in-situ gust and turbulence measurements in low altitude urban environments
  + Multirotor UAVs are promising for flying anemometer platforms
* Considerations and Challenges for Rotorcraft UAV configurations
  + Important factors: endurance, payload capacity, stability in high wind speeds, effect of flow induced by rotors on the wind measurements
  + Endurance: increase rotor swept area or reduce total mass to reduce power requirements; relative merits of batteries, fossil fuels and fuel cells.
  + Helicopters:
    - Single rotor technology, with the largest disk area for given vehicle dimensions; scale well, long endurance and large payloads possible; there is interference from downwash from rotor for wind measurements, compensating by using sensor on a tether introduces complexity due to pendulum behavior of slung load
  + Multirotor UAVs
    - Like helicopters with respect to hover and VTOL, but have lower disk area for a given platform size. Increasing rotor size reduces disk loading and increases efficiency, but reduced disk loading can also make the UAV more sensitive to gusts and could induce unwanted moments
    - Fixed pitch blades; a change in rotor velocity causes a change in thrust and attitude. Increasing the diameter of rotors can lead to increased rotational inertia and reduced ability to reject disturbances in turbulent flow. Hence smaller rotors are better for fast attitude changes, and there must be a balance of propulsive efficiency with stability and maneuverability in turbulent environments
    - Typical endurance is 15-20 minutes. The wind measurement sample times will have to be less than the total endurance. Hybrid powering configurations (fuel cells + LiPo batteries) can extend endurance for MRUAVs.
    - Discussions about quantity of rotors, use of protective bumpers, rotor separation distance and placement
    - Placement of probe tip on UAV’s frame and consequences for data collected. Prudden et al. (2016) investigated a forward-facing MHHP and analyzed the rotor-induced flow field effects; separation of 2.7 rotor diameters from front rotor hub needed.
    - Sensor mounting position on MRUAV must balance {reducing rotor-induced interference and increasing probe mount stiffness} with {reducing weight, drag and adverse control effects}.
* Existing methods for MRUAV wind measurement: must consider size, weight and impact on flight performance:
  + Inertial- and power-based methods
    - Fixed wing inertial based methods
    - Quadrotor hover capabilities:
      * pitch and roll with GPS position and velocity (Neumann et al. 2010, Neumann, Bartholmai 2015)
      * experimentally-determined drag force model (Moyan Cano 2013)
      * Inclination and angle-based wind measurement (Xiang et al. 2016, Song et al. 2016). Need detailed calibration model of the quadrotor
      * Power measurement for rotors (Marino et al. 2015)
    - Limitations: spatial resolution, frequency response
  + On-board flow sensors
    - For high frequency response 4 technologies exist: particle image velocity, hot wire anemometry, multi-hole pressure probes, laser Doppler anemometry.
    - The sensor system must not affect stability and control of the aircraft
    - MEMS sensors and GPS allow for accurate determination of vehicle attitude, heading, position and speed, then transform to the ground’s coordinate frame
    - PIV is restricted to lab environments
    - Cup / propeller anemometers are unsuitable for UAVs
    - HWA: small, mechanically simple but have calibration drift, non-linear, fragile
    - Pitot tube: accurate if aligned within 10 degrees of wind direction, can’t resolve orthogonal components
    - MHPP more robust, less fragile than HWA, better suited to outdoor measurements than PIV and LDA.
      * Some systems can measure fine scale turbulence but are expensive, need calibration and extra data capture equipment.
      * MHPPs have reduced accuracy at velocities < 3m/s due to low magnitude of differential pressure measurements (not an issue for fast moving aircraft). The effective cone of acceptance is ≈±45° for 4,5-hole MHPPs.
      * To decrease phase and amplitude distortion at high sampling rates, dynamic pressure tube lengths should be minimized
      * Minimize probe head to increase spatial resolution of flow angle measurements
    - Other attempts:
      * Multiple custom-made probes for downwash detection
      * Custom-made 2D pressure-based anemometer to provide local wind velocity estimates
      * Fixed wing MAV + 5-hole MHPP + GPS + IMU
      * Fixed-wing MAV + MHPP; this couldn’t be synchronized with the IMU experimentally
      * 5-hole MHPP + temperature + humidity sensors; custom-made probe
    - LIDAR: ground-based Doppler LIDAR anemometers can provide spatially- and temporally-resolved measurements of wind velocity and direction; they have been used on the ground (Kumer at al., 2014) and on manned aircraft (Gentry et al., 2011) and shown feasible for integration with MRUAV airframes (Elbanhawi et al., 2017).

Further remarks:

The paper suggests that quadcopter-mounted anemometry is feasible using off-the-shelf components (either HWA or MHPP technology), with limitations on accuracy and operating environments. Investigate the anemometer technology available in the lab.

# Decentralized Control of Multi-Agent Aerial Transportation System, Toumi (2017)

A dissertation completed by a former MSc student at KAUST addressing cooperative transportation using quadcopters with grippers. Control is achieved using algorithms based on invariant set theory.

# Overview

|  |  |
| --- | --- |
| **Resource Number** | **Key points** |
| 1 | General overview of the robotics. Overarching issues affecting multi-agent robotics, especially information exchange. |
| 2 | Discussion of future work is relevant for any drone solution; in future work try to build in robustness to operating environment conditions and avoid reliance on GPS. |
| 3 | Comprehensive introduction to quadrotor applications. It provides evidence that PID techniques have been used for controlling quadrotors on several occasions. There are constraints on powering and navigation capabilities. |
| 4 | High-level design requirements, comments on sensors for odometry (Indoors, laser scan odometry is more suitable; outdoors, visual-based odometry is more suitable), comments on flight modes and mission control tasks are relevant. The presentation of the design process is comprehensive and methodical - use as inspiration for the technical section of the report. Consider the breakdown of mission control tasks when designing the controller (hybrid automaton?). |
| 5 | Not entirely relevant for cooperative transport. Use of a cost function / gain function associated with the environment can feed into decision making. |
| 6 | Slightly more relevant for cooperative transport, with useful insights into the prototyping process. Problem formulation is very applicable to the Project: there are directions on which variables to focus on, performance metrics and rationale for their use of software packages.  [Testing with double integrator dynamics in MATLAB] is useful for stability analysis and convergence property observation, but gives no insight about actual behavior under real agent dynamics, hardware constraints or communication losses. |
| 7 | Direct inspiration for the Project; the scope of the Project is a different application for the hardware / software platform used in the RISC lab papers. |
| 8 | Directly relevant to the Project’s objectives. The hardware used is very similar to the RISC Lab boot camp, and incorporates monocular Apriltag detection for tracking the leader. Mocap infrastructure is required for the evaluation stage. The idea of a leader and follower is intuitive. The leader uses LQR control, but PID control can be attempted. For further consideration: reorienting the leader and follower to compensate for wind drag; using multiple drones (who would be the leaders and the followers?). |
| 9 | Cited in Gassner et al. for its formulation of dynamics. In section V, it states:  The two horizontal degrees of freedom are single-input, five-state systems. The vertical degree of freedom is a single-input, two-state system. Although simpler design methods exist for such systems, LQR is used to make the results easily transferable to the design for a circular trajectory.  Investigate implementing a subset of Gassner by simulating flight dynamics using PID controllers. Investigate and understand Lagrangian mechanics equations. |
| 10 | If pursuing the idea of a leader-follower approach, problem formulation and stability analysis is helpful. The constraints 1-4 on page 75 concerning flight dynamics should be stated explicitly in the problem formulation. They use a PID approach which can inspire controller design for the Project. |
| 11 | The paper deals with a slightly different problem (using a gripper). Comments on centralization impacting quality of control signal are important. The model derivation is clearer in section 3. |
| 12 | A rigid setup of multiple quadrotors is used to infer localization and allow for a novel combination of localization and transportation. This is likely to be unfeasible for large or bulky payloads, hence should not be used in the Project. Include a clear architecture overview, like the diagram in Figure 3. |
| 13 | A very recent survey of state of the art in cooperative transport. Lee et al. look at estimating online the weight and inertial properties of an unknown payload, building an adaptive controller, and obstacle avoidance. |
| 14 | Directly relevant to the Project, with the desired setup and clear derivations. Consult the technical report for guidance on implementation in MATLAB. |
| 15 | There is a wide listing (but not comparison) of previously-used control algorithms provided in the context of the problem. The benefits of using null-space theory are unclear, but it seems it’s used to execute competing control objectives (e.g. wind disturbance rejection, obstacle avoidance). Section 1.2; control objectives should be included in the design specification for the Project. Section 2: a hierarchy of objectives can be included in the design specification and problem formulation. Include a parameters table for simulation models. |
| 16 | Viable technology that could be useful if inter-agent localization is needed. Not many details about the software implementation and it may be too involved to emulate this system in the time available. |
| 17 | Understanding this paper requires a strong understanding of visual geometry and signal processing. Localization is not the goal of the Project, cooperative transport is. Include a table of main parameters. |
| 18 | This paper focuses on one quadrotor with a slung load. Look at the problem definition and the formulation of the physical model. |
| 19 | This work follows on from source 18, with no new information about slung load transport. Future work may benefit from adopting this approach, but see an evaluation of this approach in source 20. |
| 20 | A comprehensive look at the slung-load problem for one quadrotor. Relevant aspects: hybrid dynamical system, problem formulation, methodology. |
| 21 | The authors chose grippers over tow cables, a decentralized and cooperative framework. The derivations require advanced maths and control strategies. |
| 22 | The maths is complicated. Relevant sections include the problem formulation, the assumptions for a simplified dynamic model in section 3 and the numerical simulation’s methodology in section 5. |
| 23 | The goals are relevant. The modeling is complicated and there are no design considerations for anemometer placement. |
| 24 | This dissertation provides a comprehensive methodology and clear derivations. The setup doesn’t need an anemometer. |
| 25 | The paper discusses important considerations for design of wind speed measuring systems. Specialized equipment may make replication infeasible. |
| 26 | The survey of the field and technique is relevant for the Project but the experimental setup can’t easily be replicated (a lot of specialist hardware). |
| 27 | The format, remit and methodology are all relevant. This is a work in progress, they still haven’t correlated UAV pitch and roll with wind speed and direction. |
| 28 | Section 2 provides thorough consideration for rotorcraft UAV setups. Section 3 is a very comprehensive survey of efforts in the field of multirotor UAV wind measurement. Quadcopter-mounted anemometry is feasible using off-the-shelf components (either HWA or MHPP technology), with limitations on accuracy and operating environments. Investigate the anemometer technology available in the lab. |

# Running List of Comments

Questions:

* **How can I simulate flight of a single quadrotor in MATLAB? Gazebo?**
* How can I simulate >1 UAV in MATLAB? Gazebo?
* **How can I model the dynamics of the proposed UAV setup?**
* Will there be resonance?
* **What are the performance metrics?**
* **How much can PX4 and the RISC testbed do already for this problem setup?**
* **How can we make and use ROS packages for navigation, cooperative path planning, formation control?**
* **How can we avoid collisions between quadrotors?**
* **Will a leader-follower approach entail centralization? What if the ‘beacon’ goes out?**
* What is the bearing rigidity problem?
* What is HW design?
* **HAS ANYONE DONE DYNAMIC WIND RESISTANCE POSE COMPENSATION BEFORE?**

Topics to consider (in this order):

* Multibody dynamics modeling: standalone drones; flexible connections to the payload; PID control for dynamic motion; what are the performance metrics?
* MATLAB simulation: measure the metrics; automatic tuning; model real-life measurements and system state evolution as close as possible
* ROS transcription: adapt or create a high-level package to guide motion; a lower level algorithm can incorporate the said algorithm (if Gazebo can take it, it can be done in the lab)
* Lab tests