Defence Research and Development Canada — Recherche et développement pour la défense Canada

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Literature Review on recent advances in unmanned airlift technology

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Defence Research and Development Canada – Valcartier

Contract Report
DRDC Valcartier CR 2013-157
June 2013

Canada

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IMPORTANT INFORMATIVE STATEMENTS

Abstract

This report presents a literature review on airlift using drones. This review analyzed the publications and accomplishments of major educational and governmental research organizations.

This review showed: (1) that the scientific literature on the investigated subject is scarce and very recent (2) that the study of collaborative airlift using autonomous drones must rely initially on modeling and simulation (3) that an actuated winch might be required to ensure an advantage to multiple airlifting vehicles over a single large vehicle. Furthermore, main technologies under development are: modern control laws (LQR, adaptive, optimal, etc.), increasing the autonomy of each vehicle and the formation, modeling and simulations.

Some authors did achieve a multi-vehicular airlift mission using a lightweight payload, long cables and heavily build aerial vehicles. This indicates that the airlift concept is feasible.

Résumé

Ce rapport présente une revue de littérature concernant la levée aérienne à l'aide de drones. Cette revue a analysée les publications et accomplissements d'organisations majeures de recherches tant universitaires que gouvernementales.

Cette revue a montré : (1) que la littérature scientifique sur le sujet traité est clairsemée et récente. (2) que l'étude de la levée aérienne par des drones autonomes doit s'appuyer initialement sur la modélisation et la simulation (3) qu'un système de treuil actionné peut être nécessaire afin d'assurer un avantage à l'utilisation de plusieurs véhicules au lieu d'un seul véhicule plus gros. De plus, les principales technologies en dévelopement sont : des lois de contrôle moderne (LQR, adaptatif, optimale, etc), augmentation de l'autonomie des véhicles et de la formation.

Des auteurs ont effectués une mission de levée aérienne collaborative en utilisant une masse de faible poids, de très long câbles de même que des véhicules à forte puissance et robus-tement construit prouvant que la faisabilité opérationnelle d'un tel projet est haute lorsque des conditions suffisantes en temps et en moyens sont accordés afin d'acquérir les connaissances techniques nécessaires.

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Executive summary

Literature Review on recent advances in unmanned airlift technology:

Simon Charest; Maxime Lemonnier; Jean-Samuel Marier; Frederic Lavoie; Alexandre Morris; DRDC Valcartier CR 2013-157; Defence Research and Development Canada – Valcartier; June 2013.

Introduction or background: This contract report presents a literature review of airlift using drones. This review an-alyzed the publications and accomplishments of major educational and governmental re-search organizations working on the subject in order to establish the actual knowledge through public sources. Each research team was analyzed according to Task 1 of the SOW of copntract number W7701-103543/001/QCL and includes: (1) A review of the open sci-entific literature and government reports to identify: (a) The control and systems theoretic techniques/theories used for platform and tethered payload motion control, guidance and navigation (b) The features and limitations provided by the control and systems theoretic techniques/theories researched (c) The measures of performance used to determine if the air lift of operation is successful (d) The pros/cons of using a single air vehicle versus the use of two to four vehicles collaborating in flight to achieve autonomous airlift (AAL). (2) Identify the hardware used by those sources and must include the identification of: (a) The specific rotorcraft and airship type platforms used for airlift (b) Identify the benefits and limitations of air lift carried out with rotorcraft and airship type platforms (c) Identify the scenarios where these types of platforms have been deployed or are envisaged to be de-ployed (d) Identify the type/size/mass of loads for which they have been used (e) Identify the devices and components used onboard those platforms for air lift.

Results: The review showed that the scientific literature on unmanned airlift is scarce and very re-cent. This is an evolving field that requires a monitoring of airlift publications. A few conclusions and recommendations emerged: the study of collaborative airlift using au-tonomous drones must rely initially on modeling and simulation, investigations on the pay-load oscillations and solutions to their damping must be done as well as investigations on whether relative positioning systems between all bodies are required to provide a system that is capable of collaborative and autonomous airlift.

Significance and future plans: A set of recommendations is given. It summarizes how to achieve an integrated airlift system for scenarios involving manned and/or unmanned vehicles, autonomously or not and operating in collaborative or non-collaborative roles (a single vehicle or a team).

Sommaire

Literature Review on recent advances in unmanned airlift technology

Simon Charest; Maxime Lemonnier; Jean-Samuel Marier; Frederic Lavoie; Alexandre Morris ; DRDC Valcartier CR 2013-157 ; Recherche et développement pour la défense Canada – Valcartier ; juin 2013.

Introduction ou contexte : Ce rapport présente une revue de littérature sur la levée aérienne des drones. Cette revue a analysée les publications et accomplissements d'organisations majeures de recherches, tant universitaires que gouvernementales travaillant sur ce sujet afin d'établir l'état actuel des connaissances à l'aide de sources publiques. Chaque équipe de recherche a été analysé selon la Tâche 1 du SOW du contrat numéro W7701-103543/001/QCL et inclus : (1) La revue de littérature scientifique et de rapports gouvernementaux afin d'identifier : (a) Les systèmes et théories de contrôle utilisés pour le contrôle, guidage et navigation des véhicules et de la charge utile (b) Les caractéristiques et limites prévus par les systèmes et théories de contrôle utilisés (c) Les mesures de performances utilisés afin de déterminer si l'opération de levée aérienne est un succès (d) Les avantages et inconvénients à l'utilisation d'un seul véhicule en comparaison à l'utilisation de deux à quatre véhicules collaborant afin de réaliser un AAL. (2) Identifier le matériel utilisé par ces sources, ce qui inclus :(a) L'identification des véhicules spécifiques utilisés pour la levée aérienne (b) Identifier les avantages et limites de ces plateformes (c) Identifier les scénarios où ces plateformes ont été déployées ou envisagées d'être déployées (d) Identifier le type/dimension/masse des charges pour lesquels les véhicules ont été utilisés (e) Identifier les équipements et composantes utilisés à bord des plateformes pour la levée aérienne.

Résultats : Cette revue a démontré que la littérature scientifique sur la levée aérienne est clairsemée et très récente. C'est un domaine en évolution qui requière un suivi des publications sur ce sujet. Quelques conclusions et recommandations ont émergées : l'étude de la levée aérienne collaborative en utilisant des drones autonomes doit initialement s'appuyer sur de la modélisation et simulation, que des analyses sur les oscillations de la charge utile et les solutions pour les réduire doivent être réalisées de même que des analyses sur la nécessité de systèmes de positionnement relatif entre les véhicules et la charge utile et entre les véhicules pour rendre possible la levée aérienne collaborative et autonome.

Importance et perspectives : Une série de recommandations est présentée. Elles résument les moyens d'obtenir un système intégré de levée aérienne pour les scénarios impliquant des véhicules avec ou sans pilotes, autonomes ou non et opérants en collaboration ou non (un seul véhicule ou une équipe).

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1 Introduction

1.1 Background

This document presents a literature review on unmanned airlift by means of drones. This report is part of the deliverables of contract W7701-103543/001/QCL.

Airlift with a single drone or with a team of drones is a capability that would reduce the burden on human operators : lessen requirements in skills and in number of operators, reduce exposure to risks, and reduce fatigue. The use of multiple, coordinated unmanned aerial vehicles to carry a single load provides agility by means of a greater range of lift options, flight maneuvers, and load attitudes in addition to enabling improved fuel efficiency, especially when the full payload capability of a larger vehicle is not required.

Before loads are carried off the ground and are precisely delivered by means of one or more air platforms, a thorough investigation is required for reasons of safety, effectiveness, and cost. This is part of the motivation for contract W7701-103543/001/QCL.

1.2 Scope of this report

According to Task 1 of the SOW of contract W7701-103543/001/QCL, a scientific literature review report has to be delivered and must include:

1. A review of the open scientific literature and government reports to identify:
   (a) The control and systems theoretic techniques/theories used for platform and tethered payload motion control, guidance and navigation
   (b) The features and limitations provided by the control and systems theoretic techniques/theories researched
   (c) The measures of performance used to determine if the airlift of operation is successful
   (d) The pros/cons of using a single air vehicle versus the use of two to four vehicles collaborating in flight to achieve autonomous airlift
2. Identify the hardware used by those sources and must include the identification of:
   (a) the specific rotorcraft and airship type platforms used for airlift
   (b) Identify the benefits and limitations of airlift carried out with rotorcraft and airship type platforms
   (c) Identify the scenarios where these types of platforms have been deployed or are envisaged to be deployed
   (d) Identify the type/size/mass of loads for which they have been used

(e) Identify the devices and components used onboard those platforms for airlift

This review analyzed the publications and accomplishments of major educational and governmental research organizations working on the subject in order to establish the actual knowledge through public and open sources.

Section 2 presents various research teams working on unmanned airlift technologies. Section 3 gives other relavant research activities. Section 4 presents conclusions and recommendations.

2 Literature review

This section presents the results of the literature review. We separated the literature review by research team identified to be working on the subject. To match the requirements of Task 1 of contract W7701-103543/001/QCL (presented in section 1.2), each research team was analyzed using the following format:

Research Team A, Ref. [X,Y,Z]

Task 1.1. Theoretical background

- Task 1.1.1 Control and system theoretic techniques/theories
- Task 1.1.2 Features and limitations
- Task 1.1.3 Performance metrics used
- Task 1.1.4 Multi-MURs vs Single-MUR comparison

Task 1.2. Hardware platform

- Task 1.2.1 Aircraft type used for air lift
- Task 1.2.2 Benefits and limitations
- Task 1.2.3 Deployment scenarios envisaged or achieved
- Task 1.2.4 Payload specification
- Task 1.2.5 Devices and components used on-board

2.1 Technische Universität Berlin (Germany), Ref. [1, 2, 3]

Task 1.1 Theoretical background

Task 1.1.1 Control and system theoretic techniques/theories

- The payload-Miniature Unmanned Rotorcrafts (MURs) system is modeled as a point mass system coupled by unbendable, inelastic massless links, where mass points represent hovercraft's CoG and links represent tethers.
- An n-MUR system is captured by a common state vector capturing the $n+1$ individual states of the system, $\mathbf{x}_{sys} = \begin{bmatrix}\mathbf{x}_1 & \dots & \mathbf{x}_n & \mathbf{x}_p\end{bmatrix}^T$, where $\mathbf{x}_{1 \dots n}$ are MURs spatial coordinates and $\mathbf{x}_p$ is payload spatial coordinates. The point mass system controller determines :
  - The translational forces $\mathbf{f}^*_{sys} = \begin{bmatrix}\mathbf{f}_1 & \dots & \mathbf{f}_n & \mathbf{f}_p\end{bmatrix}^T$ needed to bring the point mass system at the desired position $\mathbf{x}^*_{sys}$ from the actual position $\mathbf{x}_{sys}$.

- The upward forces f_{i_z} to be generated by the main rotors of each aircraft and the roll and pitch moments required to orient the main rotors in the right direction.

- The lower-level controller on board helicopters is force/moments based. Figure 1 presents a block diagram describing the point mass system controller. Details about the theory are provided in [2].
- Since the MURs can sense tether's orientation (see Hardware platform) and that real life experiments showed that tethers' behavior, as seen from the orientation sensors, varies significantly from the behavior of idealized unbendable, massless link, proper signal conditioning has to be applied on sensors readings. Authors propose a linear state observer and compare it to a 4^{th} order Butterworth filter.

Task 1.1.2 Features and limitations

- Scales to an arbitrary number of vehicles.
- System wide state vector and centralized controller.
- Specific to main rotor/tail rotor type MUR.

Task 1.1.3 Performance metrics used

- Trajectory plots.
- Ability to achieve a mission under 30 to 40 km/h winds.
- Payload weight used for successful missions.

Task 1.1.4 Multi-MURs vs Single-MUR comparison

- *The construction and maintenance of high payload capacity helicopters is extremely difficult and expensive*[3], thus it may be cost effective to use many simpler aircraft.
- *The deformations of the blades on the main rotor impose the limits on increasing the main rotor diameter and the payload of the helicopters*[3], thus there may be some physical limitation on the maximum weight a rotorcraft can lift.
- Using more than one aircraft for load transport opens new possibilities in term of maximum payload capacity.
- They experimentally tested their system on a single vehicle and a team of 3 MURs. More details are given in Task 1.2.3

Task 1.2 Hardware platform

Task 1.2.1 Aircraft type used for air lift

- Helicopters with a main rotor and a tail rotor
- Main rotor : 1.8 m diameter, 1300 rotations per minute (RPM).
- Weight : 13 kg (no information if it represents the dry weight).
- Engine : 1.8 kW two-stroke gas engine.

- Onboard equipment weight : approx. 1.5 kg.
- Payload capability : approx. 3 kg.

Task 1.2.2 Benefits and limitations

- Benefits
  - Gas powered engines typically have longer flight time.
  - Can be scaled to full size helicopter more easily
  - Payload orientation sensor can be combined with tether's length to determine payload's position relative to the aircraft.
- Limitations
  - An helicopter is a naturally unstable aircraft, so it is harder to achieve precise hovering
  - More complicated mechanically (flapping rotor) than fixed pitch multi-rotor aircraft.

Task 1.2.3 Deployment scenarios envisaged or achieved

- The following deployment scenarios were achieved in experiments:
  - Experiment 1 : Single MUR transport of a payload :
    * 5 m tether, manually attached to the tether.
    * 1 kg payload.
    * Autonomous take-off, fly to about 5 m altitude with the low-level controller
    * Then the high-level controller kicks in and increase altitude to 15 m.
    * 41 m transport, straight line, no obstacles.
    * At destination, altitude is reduced to 7m and payload is automatically dropped 2 m from ground.
  - Experiment 2 : 3 MURs transport of a payload
    * Equilateral triangle shaped formation, 8m inter-vehicle distance.
    * 13 m tether, manually attached to the tether.
    * 4 kg payload.
    * Autonomous take-off, fly to about 10 m altitude with the low-level controller
    * 15 m working altitude.
    * 10 m transport "steps", straight line, no obstacles.
    * No information on payload landing.
- All missions realized outdoor, with winds of 30-40 km/h.
- 2 *YouTube* videos were posted in December 2007 on these experiments[1], [2].

[1] *Load transportation using an autonomous helicopter* is a video on experiement 1. The link to the video is `http://www.youtube.com/watch?v=J3gmzn0bSa4`

[2] *Load transportation using multiple UAVs* is a video on experiement 2. The link to the video is `http://www.youtube.com/watch?v=tl6DYWNe9ac`

Task 1.2.4 Payload specification

- Weight = 1 kg (single MUR) and 4 kg (3 MURs)
- Human intervention for hooking phase

Task 1.2.5 Devices and components used on-board

- A "Load Transportation Device", a pan-tilt gimbals system equipped with magnetic angular encoders used to sense tether's orientation, a load cell to sense tension applied on the tether and an electronically actuated tether release pin.
- Other electronics onboard : Inertial Measurement Unit (IMU), magnetometer, Global Positioning System (GPS), Wireless Local Area Network (WLAN), control computer.

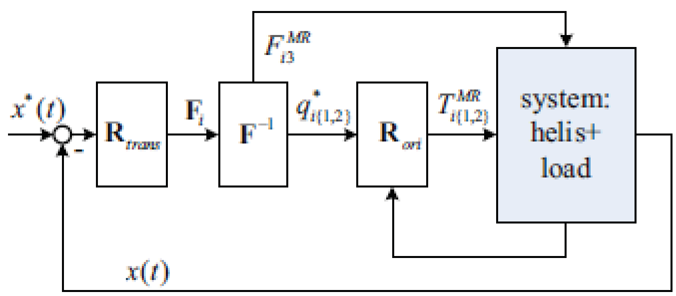


Figure 1: Collaborative controller found in [1]

2.2 Aalborg University (Denmark), Ref. [4, 5, 6, 7]

Task 1.1 Theoretical background

Task 1.1.1 Control and system theoretics techniques/theories

- Reference [5] presents the modeling of slung-load systems using constrained equations of motion (Udwadia-Kalaba). Reference [4] also gives a description of multi-vehicle systems. These equations of motion also describe cable collision and collapse (no tension).
- State estimation and sensor fusion is realized by an unscented Kalman filter (UKF). The load position is measured using an IMU and a computer vision system (one camera). The helicopter is equipped with an IMU and GPS, [6, 7]
- Oscillations of the load are damped using intentionally delayed feedback [4, 7]. Figure 2 presents a block diagram describing the delayed feedback. The theoretic tool used for such damping is called Zero Vibration and Zero Vibration Derivative input shaping.

- In addition to the above, [7] describes a simple Kinematic mapping that allows generating a trajectory for the vehicle given a payload trajectory.
- Optimal control of a payload by a single vehicle is achieved using a Linear Quadratic Regulator(LQR) [7].

Task 1.1.2 Features and limitations

- Automatic generation of oscillation damping controllers.
- Oscillation damping of the payload.
- Designed for precise control of the payload.
- Needs a linearized model of the MUR.
- Needs an "open" box controller of a certain type (Proportional Integral Derivative (PID)).
- Mainly Single-MUR oriented, but [7] also talks about the dual-MUR scenario.

Task 1.1.3 Performance metrics used

- Trajectory plots.
- Tether angle in MUR-centered coordinate (deviation from zero in roll and pitch in response to a step variation in MUR commanded position)
- Simulation and real world experiments.

Task 1.1.4 Multi-MURs vs Single-MUR comparison

- Mainly Single-MUR oriented, but [7] also talks about the dual-MUR scenario. No significant comparison is presented.

Task 1.2 Hardware platform

Task 1.2.1 Aircraft type used for air lift

- Aalborg University's AAU Corona
  - Helicopter with a main rotor and a tail rotor
  - Weight : 1 kg.
  - Engine : electric.
  - Gain-scheduled PID controller.
- GT-Max (granted by Georgia Tech)
  - Helicopter with a main rotor and a tail rotor
  - Main rotor : 3 m diameter, 1300 RPM.
  - Weight : 100 kg (no information if it represents the dry weight).
  - Engine : gas.
  - Adaptive controller

Task 1.2.2 Benefits and limitations

- Benefits
  - Gas powered engines typically have longer flight time.

  - Can be scaled to full size helicopter more easily
  - A computer vision based payload orientation sensor (presented in [6]) can be combined with tether's length to determine payload's position relative to the aircraft.
- Limitations
  - A helicopter is a naturally unstable aircraft, so it is harder to achieve precise hovering
  - More complicated mechanically (flapping rotor) than fixed pitch multi-rotor aircrafts.

Task 1.2.3 Deployment scenarios envisaged or achieved

- Initial tests are in simulation. Those tests includes:
  - In reference [5], single-UAV with two (2) cables and single-UAV with 4 cables (with an Inverted V cable pattern: two (2) anchor point on the helicopter and 4 on each corner of the payload, as shown on figure 3)
  - In reference [6], single-UAV with four (4) different slung load configurations are tested: single wire, dual wire, Inverted V , Four wire centered as shown on figure 3
  - In reference [7], single-UAV with six (6) different slung load configurations are tested single wire, dual wire, Inverted V, Inverted Y, 4 wire centered, 4 wire straight as shown on figure 4. Dual-UAV case is also briefly examined and three configurations are tested: lift pendant system, straight dual lift system, dual lift spreader bar system as shown on figure 5
- The following experiments were also realized:
  - Experiment 1 : Aalborg University's AAU Corona
    * 1.25 m tether, manually attached to the tether.
    * 0.15 kg payload.
    * Reaction to a step in position command.
    * Indoor.
  - Experiment 2 : GT-Max (granted by Georgia Tech)
    * 7 m tether, manually attached to the tether.
    * 5.5 kg payload.
    * Reaction to a step in position command.
    * Outdoor.

Task 1.2.4 Payload specification

- Weight = 0.15 kg (AAU Corona) and 5.5kg (GT-Max)
- Human intervention for hooking phase

Task 1.2.5 Devices and components used on-board

- AAU Corona
  - Tracker for position feedback provided by Vicon optical tracking system
- GT-Max (granted by Georgia Tech)
  - GPS, IMU, state estimator.

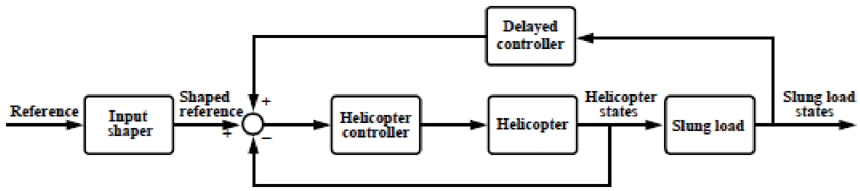


Figure 2: Delayed feedback controller found in [4]

(a) (b) (c) (d)

Figure 3: Different load configurations found in [6]. Single wire (a), Dual wire (b), Inverted V (c), Four wire centered (d).

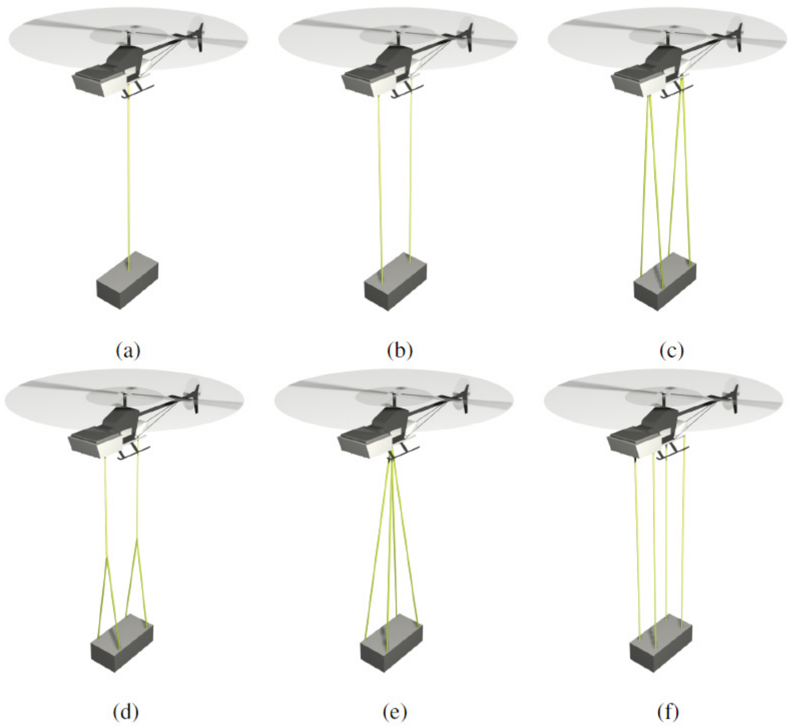


Figure 4: Six different slung load configurations found in [7]. Single wire (a), Dual wire (b), Inverted V (c), Inverted Y (d), 4 wire centered (e), 4 wire straight (f)

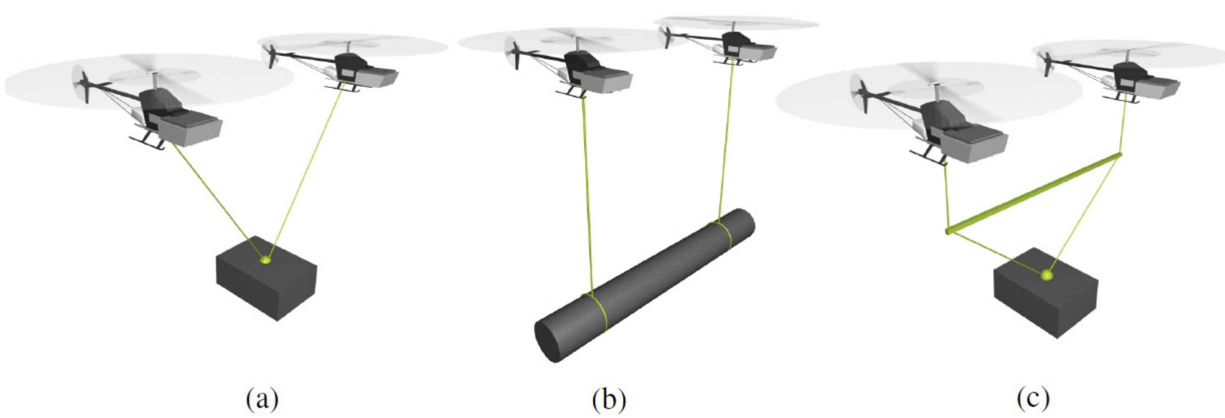


Figure 5: Three (3) different multi lift configurations found in [7]. Dual lift pendant system (a), Straight dual lift system (b), Dual lift spreader bar system (c)

2.3 DRDC high-level control for airlift (Canada), Ref. [8]

Task 1.1 Theoretical background

Task 1.1.1 Control and system theoretic techniques/theories

- Finite state machine for phase transitions (take off, autonomous hooking, lifting, flight to destination, payload landing, unhooking, MUR landing). It serves as a high-lever (outer loop) controller that sends position commands to a low-level embedded controller.

Task 1.1.2 Features and limitations

- Real-world experiments with 1 and 3 MUR but with an imaginary payload.
- Design scalable to *n* MURs.
- No simulative model, no oscillation damping.

Task 1.1.3 Performance metrics used

- Trajectory plots.
- No evaluation of payload motion: this work is used to verify the high-level finite state machine

Task 1.1.4 Multi-MURs vs Single-MUR comparison

- Using multiple MURs is a more scalable solution.

Task 1.2 Hardware platform

Task 1.2.1 Aircraft type used for air lift

- Quanser QBall X4 [8], a commercial off-the-shelf (COTS) electric quadrotor.
- Rotors span: 10 inches.
- Protective cage.
- Weight : 1.4 kg with a 380 g battery.
- Lift capacity : 100-150 g.
- PID controller dependent on global optical tracking system.

Task 1.2.2 Benefits and limitations

- Benefits
  - Naturally stable aircraft (i.e. with perfectly equivalent and equidistant motors, a perfectly balanced quadrotor would, in theory, be able to hover without controller.)
  - Mechanically simple (no cyclic swashplate).
  - Tolerant to crashes.
- Limitations

– Low lift/weight ratio

Task 1.2.3 Deployment scenarios envisaged or achieved

- The following scenarios was achieved:
  - Single and multi-MUR autonomous lifting, transport and landing of an imaginary payload (indoor).

Task 1.2.4 Payload specification

- Not applicable

Task 1.2.5 Devices and components used on-board

- Sensors : 9 degrees of freedom (DoF) IMU, downward pointing sonar
- Embedded computer : Gumstix Verdex (ARM)

2.4 GRAB Lab, Yale University (USA), Ref. [9, 10, 11]

Task 1.1 Theoretical background

Task 1.1.1 Control and system theoretic techniques/theories

- A PID controller can be used to stabilize a rotorcraft carrying a payload with a gripper.
- Modeling of the gripper as a 3 DoF translational spring and a 3 DoF rotational spring linking the payload to the rotorcraft [9, 10].
- Stability analysis using Routh-Hurwitz criterion to obtain bounds on gripper characteristics that allow the rotorcraft to remain stable while carrying a load [9].

Task 1.1.2 Features and limitations

- Method designed for near-level flight.
- Assumes high gain and fast dynamics for attitude control, small gain and slow dynamics for position control.
- Designed to be robust to grasping of objects of various shapes and mass distribution.

Task 1.1.3 Performance metrics used

- Percentage of successful grabs ([11]).
- Plots of state variables as a function of time to show behavior of the system when contact is made with an object ([10]).

Task 1.1.4 Multi-MURs vs Single-MUR comparison

- Not applicable: Single-UAV only.

Task 1.2 Hardware platform

Task 1.2.1 Aircraft type used for air lift

- T-Rex 600 ESP (Align RC, Taiwan): an electric powered helicopter.

- Helicommand RIGID COTS control system (Captron, Germany)
- Main rotor span : 1.35 m
- Maximum payload : 1.8 kg
- Uses mechanical gripper, robust to up to 100 mm misalignment with object. Random object shape, no tethers, does not require specific payload-side equipment.

Task 1.2.2 Benefits and limitations

- Benefits
  - High lift / weight ratio
  - When compared to quad-rotors, an helicopter has a large gain for controlling yaw. In [10], the author remarks that for this reason, a quad-rotor could be a poor choice when the gripper has a lateral offset.
  - Can be scaled to full size helicopter more easily
- Limitations
  - More complicated mechanically than fixed pitch multi-rotor aircraft (two rotors)

Task 1.2.3 Deployment scenarios envisaged or achieved

- Numerical simulations [10].
- Single aircraft transport of various objects with a multi-finger gripper. Figures in [11] suggest the experiments were performed outdoors.

Task 1.2.4 Payload specification

- Types of payloads investigated ([11]):
  - a softball (160 g, 89 mm);
  - a PVC tube (390 g, 280 mm);
  - a water bottle (600 g, 220 mm);
  - a wood block (700 g, 265 mm);
  - a cylinder (900 g, 390 mm).
- The aircraft was piloted manually but PID control is used for stabilization.

Task 1.2.5 Devices and components used on-board

- Sensors : IMU, Optical Camera
- Embedded computer

2.5 VT Unmanned Systems Lab, Virginia Polytechnic Institute and State University (USA), Ref. [12]

Task 1.1 Theoretical background

Task 1.1.1 Control and system theoretic techniques/theories

- Using a winch for vertical actuation only, it approximates a passive damping system for payload sway control. It is based on a control technique from Bockstedte and Kreuzer called modal coupling control, which emulates an elastic pendulum.
- The tether is assumed to be an unbendable, inelastic massless body. Which eases simulations and computations.
- The load cell/winch unit is modeled as a visco-elastic component that can recreate the behavior of a real elastic tether with elasticity adjustable in real-time.
- System identification of a simulative model of the sway damping controller (see figure 6) with real experimental data; oscillation frequency analysis.

Task 1.1.2 Features and limitations

- As the system does not act on rotational movement of the payload, it can be easily simulated as a 2D pendulum.
- Developed systems have been tested in a testbed, but were not integrated on a MUR.

Task 1.1.3 Performance metrics used

- Trajectory plots.
- Tension plots.
- Frequency response plots.
- Angle attenuation vs. winch-controlled damping ratio.

Task 1.1.4 Multi-MURs vs Single-MUR comparison

- Not applicable: Single-MUR only.

Task 1.2 Hardware platform

Task 1.2.1 Aircraft type used for air lift (Note: While the system was not yet integrated at the time of writing, the following hardware platform was detailed in [12])

- Helicopter with a main rotor and a tail rotor.
- Main rotor span: 3115 mm
- Weight: Approx. 95 kg
- Autonomy: Up to 1.5 hours with auxiliary tank (fuel-propelled)
- Speed: Up to 20 km/h, with 0.5 m/s increments

- Lift capability: not specified

Task 1.2.2 Benefits and limitations

- Benefits
  - Fuel system offers longer flight autonomy.
  - Can be easily scaled to full size helicopter.
- Limitations
  - Large size aircrafts and fuel systems are forcing an outdoor use, therefore systems like OptiTrack could not be used to simulate GPS. A civilian GPS is generally speaking less precise than an OptiTrack-like system.

Task 1.2.3 Deployment scenarios envisaged

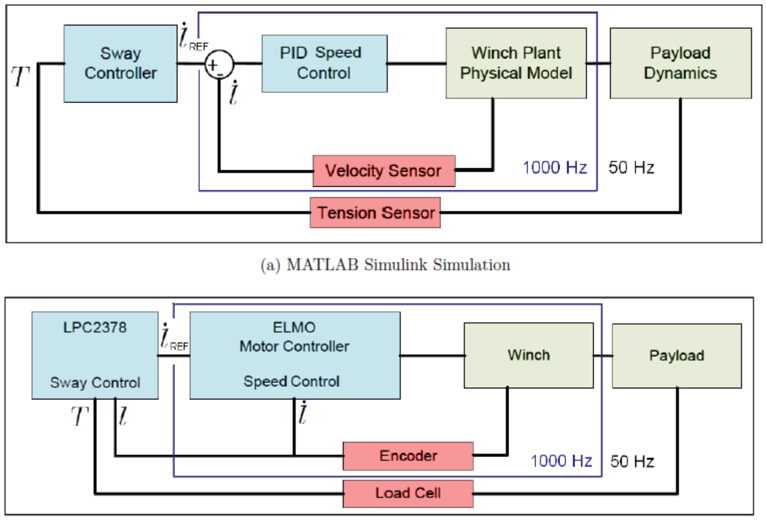
- Single aircraft transport of a Ground Sampling Robot (GSR) manually attached to the tether.
- Human intervention during takeoff and landing phase.
- Transportation of the GSR to a designed GPS waypoint location.
- Continuous tension on the tether during the deployment of the GSR.
- Return to starting location after the mission has been executed.

Task 1.2.4 Payload specification

- Weight: 8 kg
- Payload is already attached before takeoff.

Task 1.2.5 Devices and components used on-board

- WePilot Automated Flight Control System, with GPS waypoint execution and hovering capabilities.
- Tethering payload system
  - Winch
    * Motor controller: Elmo Whistle motor controller and incremental position encoder.
    * Motor: Maxon RE40 DC brushed motor.
    * Tension feedback circuitry: Omega LC103 load cell. load cell.
    * Electromagnetic brake.
  - Reel and tether apparatus.
  - Tether emergency release mechanism.
  - System control unit : NXP LPC2378 ARM7 with embedded LabView.



(a) MATLAB Simulink Simulation

(b) Actual Hardware Setup

Figure 6: Winch controller architecture found in [12]

2.6 National Aeronautics and Space Administration (NASA), Ames Research Center (USA), Ref. [13]

Task 1.1. Theoretical background

Task 1.1.1 Control and system theoretic techniques/theories

- Generic mathematical formulation parametrized by degrees of freedom and force constraints (elastic and inelastic) presented as a *n*-body theoretical framework.
- Simple helicopter model with single main rotor and tail rotor.
- Based on D'Alembert's principle for holonomic constraints.
- Computational cost for each simulation method is considered and analytically determined.
- Presents derivation for both non-linear and linearized system.
- Numerical stability is considered.

Task 1.1.2 Features and limitations

- Extensive mathematical modeling of a large class of single and multi-MUR systems (see figure 7).
- Considers elastic and inelastic constraints (tethers).
- Complete example mathematical models detailed for single-rotor MUR, dual-rotor MUR (dual tether) and dual MUR airlift simulations.
- No control theory, no controller presented.
- No state estimation, no sensor models.

Task 1.1.3 Performance metrics used

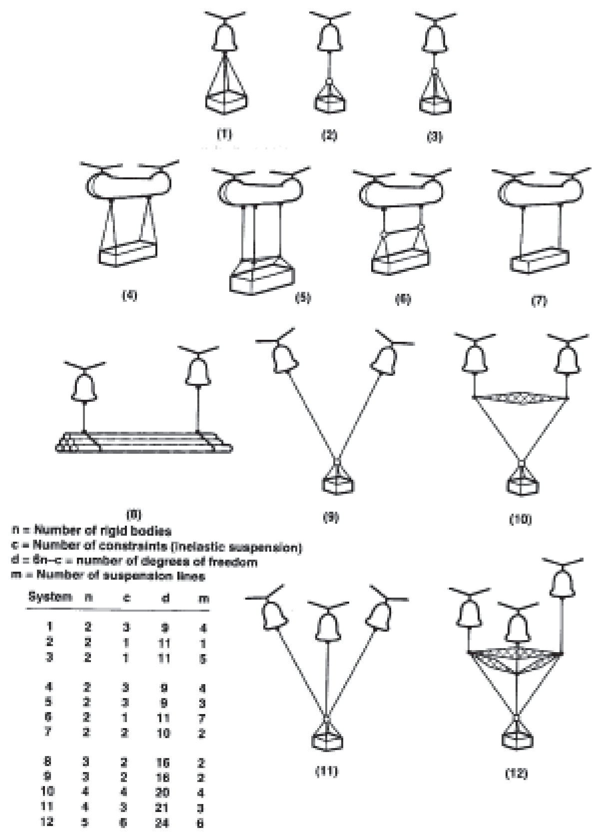
- Theoretical computational cost comparisons

Task 1.1.4 Multi-MURs vs Single-MUR comparison

- Multi-aircraft airlift have been advocated as an alternative to larger single-aircraft to reach higher payload since the beginnings of airlift experimentation.
- In a lot of situations, there is a desire to obtain larger airlift capacity using locally available helicopters, in other words, to combine their lifting capacity.

Task 1.2. Hardware platform

- Not applicable: simulation only.



System	n	c	d	m
1	2	3	9	4
2	2	1	11	1
3	2	1	11	5
4	2	3	9	4
5	2	3	9	3
6	2	1	11	7
7	2	2	10	2
8	3	2	16	2
9	3	2	18	2
10	4	4	20	4
11	4	3	21	3
12	5	6	24	6

Figure 7: Different airlift formations found in [13]

2.7 University of New Mexico, Albuquerque (USA), Ref. [14]

Task 1.1 Theoretical background

Task 1.1.1 Control and system theoretics techniques/theories

- Simulation:
  - Quadrotor dynamics model
  - Suspended load model
  - Adaptive control
  - Dynamic programming for optimal trajectory generation
- Experiment:
  - Baseline attitude controller is a feedback-linearizing controller and linear control algorithm :
    * In "X" and "Y" : lead-lag in position and in velocity
    * In "Z" : lead-lag in position
    * In yaw : PI controller
    * No information on pitch and roll
  - Trajectory reference value from optimal trajectory.
  - Baseline controller is implanted in cascade with the AscTec AutoPilot on-board flight control unit.

Task 1.1.2 Features and limitations

- Single-MUR
- The adaptive controller and optimal trajectory are capable of damping oscillations but not able to reduce the residual ones.
- Implementation is not trivial and requires heavy computation.

Task 1.1.3 Performance metrics used

- Trajectory plots
- Simulation vs experiment
- Payload angles
- Power spectral density and total power of the load-displacement signals

Task 1.1.4 Multi-MURs vs Single-MUR comparison

- Single-MUR only.

Task 1.2 Hardware platform

Task 1.2.1 Aircraft type used for air lift

- AscTec Hummingbird quadrotor
  - Max. payload: 200 g
  - Min. take-off weight: 510 g

Task 1.2.2 Benefits and limitations

- Simple and easy to repair
- Low lift and crash survivability

Task 1.2.3 Deployment scenarios envisaged or achieved

- The following scenario was achieved:
  - Multiple waypoint with obstacles, including:
    - Cubic polynomial position trajectories for initial simulation using adaptive control
    - Optimal swing-free trajectory in simulation using adaptive control
    - Cubic polynomial position trajectories in experiment using baseline controller
    - Optimal swing-free trajectory in experiment using baseline controller

Task 1.2.4 Payload specification

- Mass of 47 g
- Cable length of 62 cm

Task 1.2.5 Devices and components used on-board

- Tracker for VICON™optical tracking system
- AscTec AutoPilot on-board flight control unit (CPUs)
- R/C radio controller
- Barometer, IMU, GPS

3 Other relevant activities in unmanned airlift research

The following activities are related to unmanned airlift are not included in the previous subsections as they are not from any of the major research teams identified, but are still related to this project:

- Reference [15] presents Lockheed Martin's K-MAX Unmanned Helicopter web page and [17] presents the Wikipedia entry of this helicopter. This helicopter is a modification from a manned helicopter (build by Kaman Aircraft of Bloomfield, Connecticut, USA) to a remote controlled unmanned aerial vehicle. According to Wikipedia: "*the K-MAX Unmanned Multi-Mission Helicopter, is planned for hazardous missions. It could be used in combat to deliver supplies to the battlefield, as well as civilian situations involving chemical, biological, or radiological hazards. A prototype of this was shown in 2008 for potential military heavy-lift resupply use, and again in 2010*". This platform is currently used only as a single-UAV airlift platform. Figure

- Reference [16] studies a setup where the landing gear of an helicopter has been modified to include a cable-suspended robot as shown on figure 9. The helicopter and the cable-suspended robot are controlled separately. The helicopter controller has a cascade structure with a slow and a fast controller. The slow controller takes position commands and produces attitude commands; the fast controller stabilizes the attitude command produced by the slow controller. The cable robot control is implemented with a sliding-mode controller. This system was only tested in simulation.

- Reference [18] is a PhD thesis that studies the rejection of wind disturbances by an helicopter controller. The strategy is to anticipate the effect of disturbances caused by wind on the rotorcraft (feedforward control). The disturbance is estimated using a parametric model. No tethered payload is involved in this research and the focus appears to be on simulation, rather than empirical evaluation. This research is nevertheless relevant to airlift since it is known from experience acquired by Numérica Technologies Inc. on previous projects, such as [19], that aerodynamic perturbations can significantly affect the behavior of many small MURs flying close to each other.

- Reference [20] is a source identified while investigating the modeling of a winch mechanism such as in [12] and [16]. Reference [20] is a patent filed in May 2009 on the subject of airlift. Main features of this patent includes: system and method to control a team of air vehicles in an airlift mission. The system includes the swarm of vehicles and the tethers. Each vehicle is autonomous and stabilized using unspecified control laws and sensors. The swarm is guided with unspecified sensors and communication devices to follow the commands of a leader or pilot which is autonomous or not. The methods to control the multi-UAV lifting system are through inputing a series of payload waypoints. Then, these waypoints are used by the swarm controller to generate individual waypoint. Then, each vehicle's control system moves the air vehicles to these individual waypoints. This reference includes formation geometries, high-level and low-level control schematics, etc.

- Reference [21] is a technical memorandum by Ahmed Ghanmi and Abderrahmane Sokri from Centre for Operational Research and Analysis (CORA), Defense Research and Development Canada (DRDC), Ottawa, Canada, that talked about the need from the Canadian Forces to consider airship technologies. The airship technologies are not yet well covered in practice, and this memorandum is based upon theoretical analysis. Also, it cover mainly operational cost and time compared to conventional aircraft, but it has been found to minimize the complexity and operational costs of airships, such as comparing fuel consumption without considering Helium refilling necessity, neither considering infrastructural requirements.

  The technology could still be useful for heavy lift, but the concepts are still under development. For this reason and because the technical memorandum doesn't include unmanned neither collaborative vehicles, the summary will cover only main ideas of airship covered by Ghanmi and Sokri. The analysis of this reference is done as in section 2:

  Task 1.1. Theoretical background

  Task 1.1.1 Control and system theoretic techniques/theories
  - N/A: manual control

  Task 1.1.2 Features and limitations
  - Airship for cargo purposes are still in scale model prototypes.
  - Analysis are made from theoretical data on airship technical performances only.

  Task 1.1.3 Performance metrics used
  - Cost per tonne effectiveness
  - Time responsiveness

  Task 1.1.4 Multi-MURs vs Single-MUR comparison
  - Not applicable: single vehicle only

  Task 1.2. Hardware platform

  Task 1.2.1 Aircraft type used for air lift
  - No real experimentation has been conducted.
  - Simulation of logistics lift cost and time, using SkyCat hybrid airship.
  - Theoretic lift capability: up to 200 tonnes, depending on the model.

  Task 1.2.2 Benefits and limitations
  - Benefits

    * High lift capability
    * Low fuel consumption
    * Can land on ground or water
    * Capability of hovering
    * Can takeoff and landing can be achieved as aircraft or vertically.
  - Limitations
    * Low speed
    * Low flight ceiling
    * Additional cost for Helium filling. Also, the price of helium jumped over the last years[3] and the tendency don't seem to reverse.
    * Fully capable heavy lift airships haven't yet been built.
    * Even if the airship does not necessary needs a runway, it would still requires a gravel landing zone of 500 to 1500 meters of radius, depending on the payload.

Task 1.2.3 Deployment scenarios envisaged
  - Revitalization of camps in Northern Canada
  - Surveillance operations

Task 1.2.4 Payload specification
  - Theoretic weight capacity: up to 200 tonnes
  - Human intervention for loading/unloading

Task 1.2.5 Devices and components used on-board
  - The theoretic full scale model is man-controlled.
  - The 1/6 linear scale model is remote-controlled, but no information is provided.

[3] http://www.weldingandgasestoday.org/index.php/2012/04/a-look-at-rising-helium-prices/

Figure 8: Lockheed Martin’s K-MAX doing a single-UAV airlift mission, [15]

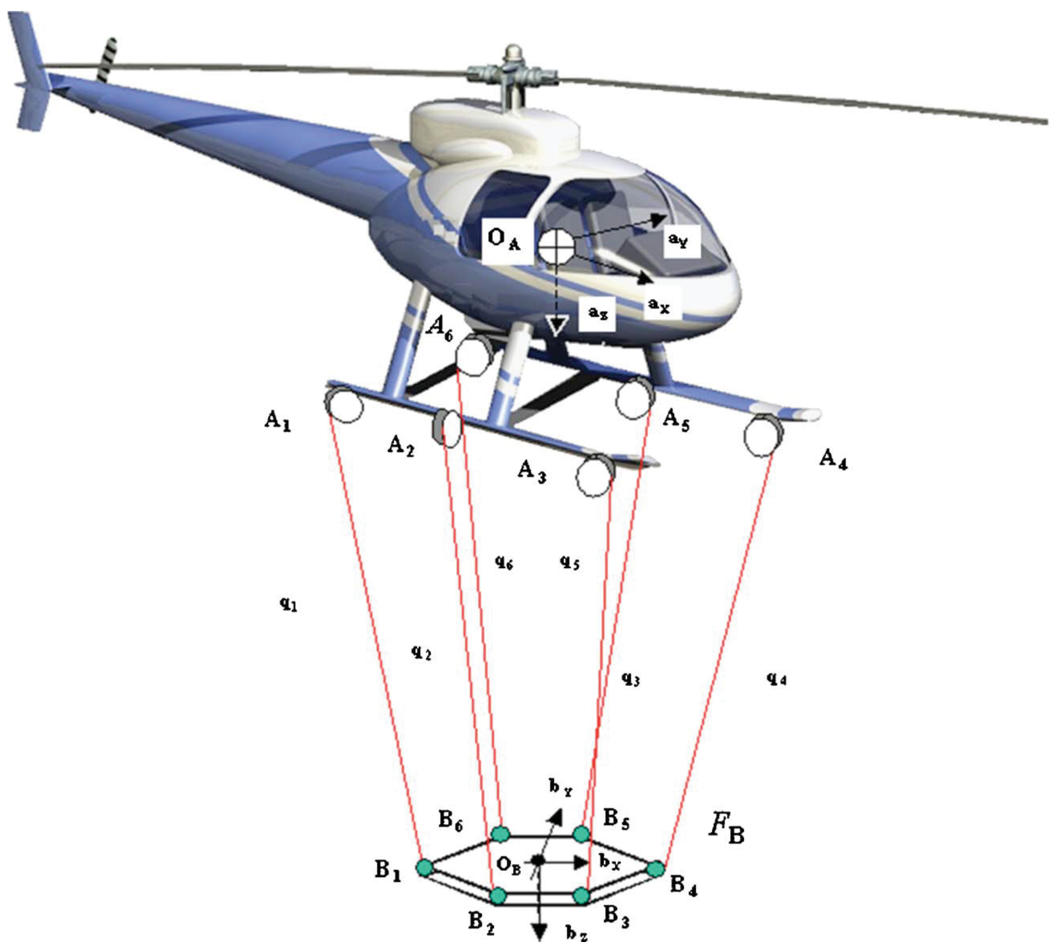


Figure 9: The modified helicopter presented in [16]

4 Conclusions, recommendations and action plan

4.1 Conclusions

In light of this literature review, we have reached to the following conclusions :

1. As stated in [22] and our results, the scientific literature in the field of autonomous airlift is relatively scarce and most of the articles on the subject are very recent.
2. While some authors propose specific oscillation damping strategies (section 2.2 and 2.5) other teams show that, by its nature, a PID controller may damp payload oscillations (section 2.4 and 2.1)
3. All research teams resorted to simulation to observe a system's behavior. The simulations range from simple pendulum simulation (section 2.5) to complex helicopter model with swashplate and cyclic flapping simulation (section 2.2).
4. All teams that considered multi-vehicle airlift modeled system's state as a large vector of 6-DoF mass points, representing the MURs and the payload. Most teams considered inelastic tethers.
5. All teams that included a flight controller in their work used an inner loop/outer loop controller scheme.
6. One team (section 2.2) performed vehicle-payload relative positioning using computer vision and a payload-bound IMU, but none performed inter-vehicle relative positioning. Another team (section 2.4) planned to use computer vision to help payload grappling.
7. The team presented in section 2.4 performed autonomous grappling but none has performed autonomous hooking of a tether on a payload.

4.2 Recommendations for way ahead

1. Continue monitoring of the scientific literature and include any relevant information in future publications related to contract W7701-103543/001/QCL.
2. Investigate the damping capabilities of a normal PID flight controller to assert the necessity of sway damping techniques. Possible means to do this using a single UAV in an airlift mission and/or high fidelity simulations using powerful simulation tools (such as for example MSC Adams, Gazebo, X-Plane (or to some degree MATLAB/Simulink), etc.). This would allow us to evaluate the issue of cable vibration and study possible ways to damp it if a PID is not enough to fulfill our requirements. This would mean to investigate the usefulness of an actuated winch for oscillation damping as proposed by

[12] and possibly to design or at least propose design requirements for a tether orientation sensor hardware.

3. Develop a high-fidelity simulator for the multi-MUR airlift system with the following specifications :
   - Initially, model tethers as massless, unbendable links.
   - Initially, model MUR and payload as rigid bodies.
   - Make the simulator computationally efficient enough to be used onboard MUR's embedded computer. The flight controller could make good use of an online simulation model to generate commands, such as in [23].
   - Model MUR's controller in the simulator.
   - Identify simulator's parameters using real MUR flight data, in order to improve fidelity and to allow controller design/tuning such as in [4]. Approximate simulative model by linearization around operating point in order to help automated controller design techniques such as LQR.
   - Simulate MUR sensors, such as in [12].
   - The simulator could benefit from object-oriented modeling to achieve higher fidelity and customization. Giving the possibility to easily modify the vehicles (or to add multiple kinds of vehicles in a simulation), their models (from point mass to fully integrated flexible bodies passing through rigid body), components, sensors, environment, etc.
4. Investigate the necessity of vehicle-payload relative positioning systems as well as vehicle-vehicle relative positioning systems. If proven to be useful and/or absolutely required, design or at least propose design requirements for such systems.
5. Investigate formations of vehicles under perfect, and possibly degraded flight conditions exhibiting multiple geometries. Reference [23] used a large cable length and inter-MUR distance ratio to achieve the most effective performances.

Annex A: List of key acronyms

AAL	Autonomous AirLift
CoG	Center of Gravity
COTS	Commercial off-the-shelf
DoF	Degrees of Freedom
GPS	Global Positioning System
GRAB	Grasping & Manipulation, Rehabilitation Robotics and Biomechanics
GSR	Ground Sampling Robot
IMU	Inertial Measurement Unit
LQR	Linear Quadratic Regulator
MUR	Miniature Unmanned Rotorcraft
PID	Proportional Integral Derivative
RPM	Rotation Per Minute
UAV	Unmanned Aerial Vehicle
UKF	Unscented Kalman Filter
WLAN	Wireless Local Area Network

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This report presents a literature review on airlift using drones. This review analyzed the publications and accomplishments of major educational and governmental research organizations.

This review showed: (1) that the scientific literature on the investigated subject is scarce and very recent (2) that the study of collaborative airlift using autonomous drones must rely initially on modeling and simulation (3) that an actuated winch might be required to ensure an advantage to multiple airlifting vehicles over a single large vehicle. Furthermore, main technologies under development are: modern control laws (LQR, adaptive, optimal, etc.), increasing the autonomy of each vehicle and the formation, modeling and simulations.

Some authors did achieve a multi-vehicular airlift mission using a lightweight payload, long cables and heavily build aerial vehicles. This indicates that the airlift concept is feasible.

Ce rapport présente une revue de littérature concernant la levée aérienne à l'aide de drones. Cette revue a analysée les publications et accomplissements d'organisations majeures de recherches tant universitaires que gouvernementales.

Cette revue a montré : (1) que la littérature scientifique sur le sujet traité est clairsemée et récente. (2) que l'étude de la levée aérienne par des drones autonomes doit s'appuyer initialement sur la modélisation et la simulation (3) qu'un système de treuil actionné peut être nécessaire afin d'assurer un avantage à l'utilisation de plusieurs véhicules au lieu d'un seul véhicule plus gros. De plus, les principales technologies en dévelopement sont : des lois de contrôle moderne (LQR, adaptatif, optimale, etc), augmentation de l'autonomie des véhicles et de la formation.

Des auteurs ont effectués une mission de levée aérienne collaborative en utilisant une masse de faible poids, de très long câbles de même que des véhicules à forte puissance et robus-tement construit prouvant que la faisabilité opérationnelle d'un tel projet est haute lorsque des conditions suffisantes en temps et en moyens sont accordés afin d'acquérir les connaissances techniques nécessaires.

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unmanned aerial vehicles; autonomous airlift; collaborative airlift; airlift

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